TOXIC GAS LEAKAGE DETECTION SYSTEM USING INDUSTRIAL SENSORS AND WIRELESS SENSOR NETWORK

BY

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To my parents

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LIST OF ABBREVIATIONS

AC	Alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
AES	Advanced Encryption Standard
BLS	Bureau of Labor Statistics
CH_4	Methane
CL	Ceiling Limit
CO	Carbon(II)Oxide
CSMA-CD	Carrier Sense Multiple Access With Collision Detection
CuO	Copper oxide
DC	Direct Current
EM	Electromagnetic
EMF	Electromotive Force
FBG	Fiber Bragg Grating
FFD	Full Function Device

FPGA	Field Programmable Gate Array
GPS	Global Positioning System
H_2S	Hydrogen Sulfide
ISM	Industrial, Scientific and Medical
LED	Light Emitting Diode
LEL	Lower Exposure Limit
LPG	Liquefied Petroleum Gas
MAC	Medium access
MCU	Micor-Controller Unit
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NEMA	National Electrical Manufacturers Association
NMEA	National Marine Electronics Association
NPW	Negative Pressure Wave
OGI	Oil and Gas Industry
OSHA	Occupational Safety and Health Administration
PC	Personal Computer
PCB	Printed Circuit Board
PHY	Physical Layer
PIR	Pyroelectric InfraRed

PSU	Power Supply Unit
RAM	Random Access Memory
RF	Radio-Frequency
RFD	Reduce Function Device
RFID	Radio-Frequency Identification
RTOS	Real-time Operating System
SMS	Short Message Service
SnO_2	Tin oxide
STEL	Short-Term Exposure Limit
STP	Standard Temperature and Pressure
TDMA	Time Division Multiple Access
TLV	Threshold Limit Value
TWA	Time Weighted Averag
UART	Universal Asynchronous Receiver/Transmitter
UEL	Upper Exposure Limit
USCSB	United State Chemical Safety Board
WGSN	Wireless Gas Sensor Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Networks

THESIS ABSTRACT

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TITLE OF STUDY:	Toxic Gas Leakage Detection System Using Industrial Sensors and Wireless Sensor Network
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One of the key causes of accidents in Oil and Gas Industries is the leakage of toxic and/or combustible gases. Due to the high fatality risk of such accidents it is necessary to develop gas sensors that are cheap, reliable and easy to use. The best way to develop these type of gas sensors is through the use of Wireless Sensor Network (WSN). WSN as the name implies is a wireless network of battery powered sensors that are deployed in an environment for sensing. It is estimated that WSN market will grow to $1.8 billion by 2024. This can be attributed to the robustness of their network, ease of use and low maintenance requirement. In this thesis, a WSN gas sensor has been developed for industrial applications, especially oil and gas industry. The sensor is developed with adaptive sleep cycle such that it sleeps for longer period (2min) when their is no gas leakage and sleeps for shorter *periods (1min) when there is gas leakage. In this research, we are able to show that a durable battery-driven wireless industrial gas sensor with long life time can be achieved through energy harvesting and adaptive duty cycle.*

CHAPTER 1

INTRODUCTION

1.1 Introduction

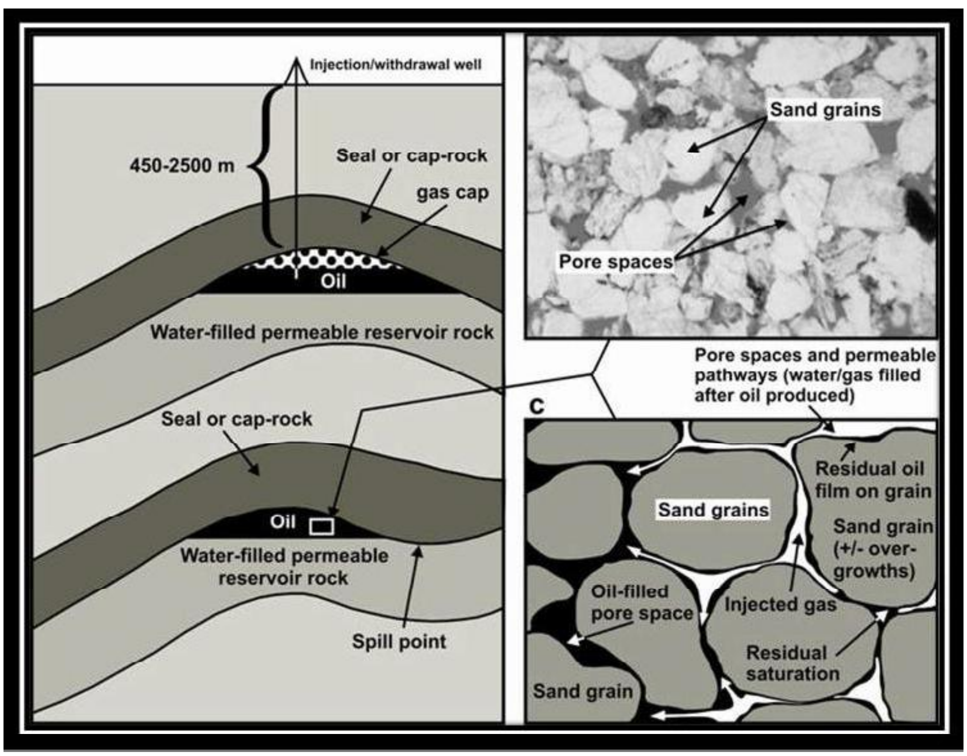

Figure 1.1: Formation of crude oil, courtesy of barryonenergy.wordpress.com.

Crude oil, also known as "Petroleum", is a mixture of several hydrocarbons that occur naturally within the earth crust [1]. Although real production began in August 27, 1859, usage of petroleum could be traced back to 5 - 6 thousand years before Christ [2]. It finds application in; medicine, military, household, transportation and the list goes on. Crude oil is formed as a result of accumulation of animals and plants that died millions of years ago and fell to the bottom of the sea. These remains were covered by mud, which eventually becomes rock, thus forming a seal. The rock exerts pressure on the dead animals and plants, thereby generating heat between 60–120^{0}C [3]. Together, the heat and the pressure in the absence of Oxygen turned the remains into crude oil. Also, if the trapped organic matter is heated to temperatures greater than 120^{0}C gases are formed (see: Figure 1.1) [4]. Some of these gases are; Carbon monoxide, Sulfur(IV)Oxide, Hydrogen Sulfide and Nitrogen Oxides.

However, most of these gases are either toxic, combustible or both [5]. Several accidents have occurred due to these gases, for example; Partridge-Raleigh Oilfield fire incidence of 5th June, 2006. A fatal explosion took place at a rural oil production field of Partridge-Raleigh in Raleigh Mississippi, killing three contractors and severely injuring one. The accident occurred while the contractors were standing on top of a series of four oil production tanks. The contractors were connecting the third and the fourth tank when a welding tool ignited flammable vapors from the tanks [6]. Another gas related accident took place on April 20th, 2010 in the Gulf of Mexico. Eleven workers died and several others injured due to a blowout as a result of several "*Kicks*" on the *Deepwater Horizon* oil rig [7]. A kick is a sudden and unplanned release of well fluids (especially gases) into a wellbore [8]. This is just a hint of gas related accidents in oil and gas industry. For more cases on gas related accidents refer to [9] [10]. It is found that these accidents are either due to total absence of gas sensors in operation sites or lack of their continuous presence (throughout the time of operation) in the area [11]. In an effort to avoid such accidents, safety measures to curve the risk of gas related accidents are recommended by United State Chemical Safety Board (USCSB) [12] and regulations are passed by Occupational Safety and Health Administration (OSHA) [13].

In view of the immense importance of these sensors, many researchers have over the years put effort in developing efficient, cheap, scalable and easy to use gas sensor in order to ensure the safe working atmosphere. Petersen *et al.* [14] [15] recommended the use of Wireless Sensor Networks (WSN) to boost safety in Oil and Gas Industry (OGI). WSN is a network of tiny sensors with limited resources that are deployed in an area for fine grain sensing. For more details on WSN refer to Section 2.2 of this document. The authors further suggest technical requirements for applying WSN in OGI, they proposed that wireless technology for OGI should:

1. Be in the Industrial, Scientific and Medical (ISM) band.

2. Contain open communication protocol.

3. Have a long battery lifetime.

4. Be able to coexist with other wireless network.

5. Be secured and have fail safe mechanism.

6. Have a quantifiable performance and the behavior should be predictable and

7. Be easy to setup.

Wang *et al.* [16] mounted a laser source, a laser spectrum analyzer and an optical sensor on a vehicle. The system scans for micro-leakage as the vehicle moves along the pipe. The obvious problem with this system is that it is somewhat manual and impractical for very long pipelines. Zhang *et al.* [17] developed a pipeline detection system for long distance pipeline based on optic fiber sensor. The optical fiber used for both communication and sensing is buried along with the pipe. Whenever a pipe breaks, stress waves are propagated along the surface of the pipe. These waves come in contact with the sensors and they interfere with the light wave in the fiber. The interferance is measured with an interferometer and suspected pipe leakage is reported to a central computer. Negative Pressure Wave (NPW) is used by [18] to detect and locate pipe leakage, while [19] developed pipe leakage detector using a more sophisticated Fiber Bragg Grating (FBG) sensor. The sensor detects leakage by sensing the pressure on the surface of the pipe. The authors conclude that even though this technique is expensive, it is more accurate than a conventional pressure sensors.

Jian *et al* [20] developed a sensor network using Zigbee technology. The network of sensors transmit information to a central computer known as the *Monitoring Server* through a *Monitoring master station*. The Monitoring master station is responsible for managing the Zigbee network as well as sending alert messages in the form of SMS to enlisted phones. The monitoring server on the other hand, is responsible for processing and storing information. Similar implementations of gas detection systems are further discussed in the *Literature Review* in Section 3.2 of Chapter 3.

Our research is aimed at developing a complete solution for energy-efficient gas leakage detection system for OGI, especially out door applications like the oil rigs, oil exploration and oil transportation. The system senses the presence of gas and transmit the readings to a central computer in a multi-hop fashion. Furthermore, the system has the ability to automatically or manually close the concerned valve. The requirements for applying WSN in OGI mentioned earlier were strictly followed during the development of this system.

1.2 Aim and Objectives

The aim of this work is to develop a toxic gas detection system using WSN that is: acceptable in OGI, can be deployed in remote areas and has the ability to control gas flow by closing pipe valves through wireless actuator in the event of leakage. In order to complete this project the following objectives have to be achieved;

1. Development of scalable and durable wireless sensor network capable of sensing and measuring gas leakages.

2. Development of self-check system, that is capable of diagnosing the network by checking the network nodes ability to transmit data and battery level.

3. Development of control system that can monitor sensor activities.

4. Development of actuator that can be remotely controlled by either the sensors or the network administrator.

1.3 Significance

Bureau of Labor Statistics (BLS) [21] reported that OGI accounts for 70% of fatal occupational injuries in the private mining industry in US in 2011 alone. In addition, employment rate in the industry has grown by 71% between 2003 and 2011, this made the development of cheap but reliable safety equipment necessary. A technology best fit for the aforementioned requirements is WSN.

As pointed out by [22], WSN has emerged as a key technology for accelerating oil and gas exploration and advancing the latest extraction techniques. Furthermore, oil and gas exploration, production and pipelines made up 27% of the global industrial WSN market in 2011 [23][24]. As such, the significance of toxic gas detection system using WSN cannot be overemphasized. Some of the importance of this research are;

1. The system will significantly cut down rate of fatal accidents, thereby increasing income and reputation of OGIs.

2. The system will cut down cost of managing oil facilities that are in remote and hazardous locations.

3. The system will provide ease of; use, deployment and maintenance of the installed system.

4. Due to WSN's flexibility and scalability, it can allow easy upgrade or introduction of new sensors. Moreover, they can support temporary installation.

5. Wireless sensor nodes are cheap and support redundancy which is very important in OGI.

6. The use of WSN will provide easy to use applications, thereby cutting down on manpower and training.

1.4 Methodology

The system is designed to measure the amount of the toxic gas present in a given area. The sensor nodes periodically sense the presence of gas in the atmosphere. The nodes then send the instantaneous quantity of the gas in the atmosphere and the location of event to the gateway which in return notifies a central user through a computer connected to the gateway. In the event of gas leakage, the sensor node sends the gas level and at the same (if set to automatic) the system will close the valves thereby preventing disaster.

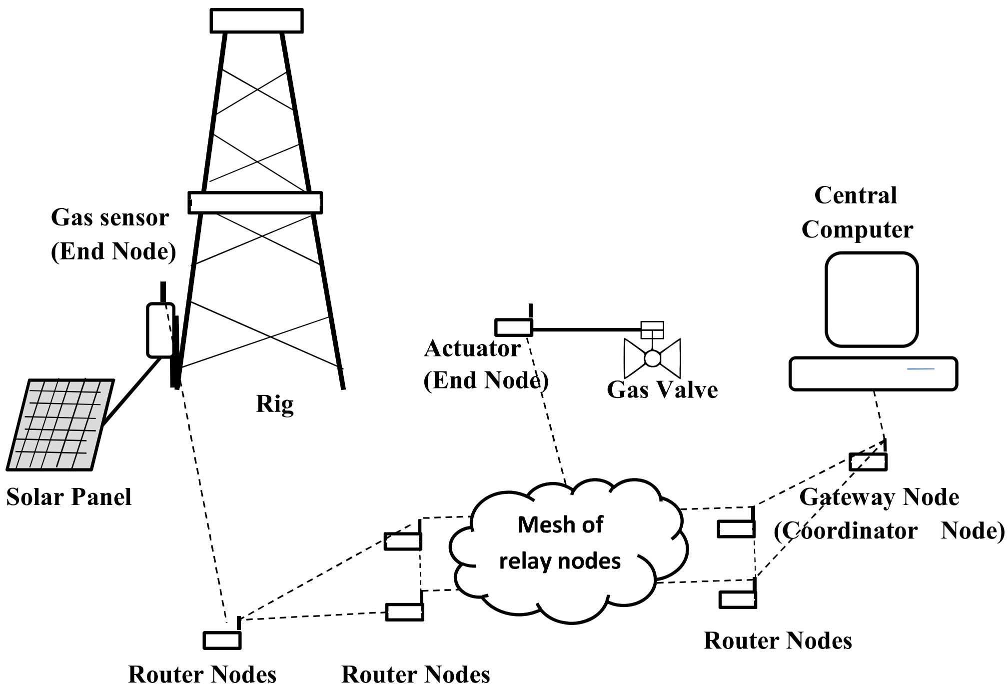

Figure 1.2: The structure of the proposed system.

Assuming there is a rise in toxic gas level in Figure 1.2, the gas sensors encased in a NEMA (National Electrical Manufacturers Association) 4 explosion-proof casing calculates the level of toxic gas in the environment and then send signal to the Control Center through the sink node. The sensor node also collects the gas reading and passes it to the nearest routing node. The data is relayed until it reaches the site office or sink node, where it is further processed. An energy efficient protocol is chosen for this purpose.

Finally, the computer at the control station can send data to a database in the internet where it can be readily accessed by authorized staff of the company from anywhere at any time. This system can be divided into hardware and software component.

1.4.1 Hardware

The hardware components of the system are basically divided into four basic, viz;

Industrial-sensor

As part of this project an Industrial grade sensor is developed. The sensor is encased in a NEMA 4 explosion-proof [25]. The sensor is designed to contain a Hydrogen Sulfide (H_2S), Methane (CH_4) and Carbon(II)Oxide (CO) sensors are enclosed in the casing. A GPS module is added for localization and an MCU is also included for processing the data and transmitting it through the networks.

End node

These are nodes connected to an electronic valve. These nodes also consist of Microcontroller, a GPS module, a relay node and a wireless communication module. This node closes valve whenever a command to do so– or the gas level has reached certain threshold.

Relay node

These are sensor nodes with Microcontroller Unit (MCU) and a wireless communication module. Their main function is providing medium for transmitting data between the end nodes and the coordinator.

Coordinator node

The coordinator is made up of an MCU and a wireless communication module. It is responsible for setting up the network as well as serving as a gateway between the sensor network and the workstation.

1.4.2 Software

Two types of software were developed in this research; the first software is embedded in the microcontrollers, which are design to control gas sensing, routing of data and forwarding of data to a workstation. The second software is design to process data on the workstation so as to enable the user to visualize location of gas leakage and decide the next line of action.

1.5 Thesis Overview

The documentation for the research is broken down into six (6) chapters; Chapter 1 provides reader with an introduction and significance of the research. It also gives the reader a summary of how the research was carried out.

In chapter 2, a theoretical background of all the paraphernalia information the reader needs in order to understand the remaining part of the project is given. This includes an overview of Zigbee protocol, Toxic gases, how they are formed, how they are detected and their scale of measurement. Some introductory information on actuators used in the oil and gas industry is also given.

In chapter 3, literature review of state-of-the-art gas detection systems that other researchers developed is discussed.

In chapter 4 the design of our proposed system is unveiled in details. The chapter also consists of the design and analysis of; the sensor nodes, the actuators and the operation of the overall system.

In chapter 5, explanation of experimental setup and the readings recorded are presented. Furthermore, the chapter discusses the implications of these readings.

In chapter 6, presents conclusions drawn regarding the proposed system with regards to the data presented in chapter 5 above.

CHAPTER 2

BACKGROUND

2.1 Introduction

This chapter is designed to provide the reader with introductory information on the different aspects of this research in order to prepare him for chapters to come. Here, the reader is taught about the toxic and combustible gases found in the Oil and Gas Industry (OGI). In this document, OGI processes encompass oil (petroleum) and gas; exploration, extraction, refining, transportation and marketing. Moreover, brief introduction on Wireless Sensor Network (WSN), its applications and market trends is also provided. The reader will also find information on different gas sensors available in the market, how they work and their characteristics. Finally, industrial grade actuators used in the OGI are also discussed herein.

2.2 Wireless Sensor Network (WSN)

Wireless Sensor Networks (WSN) is a network paradigm where tiny wireless devices equipped with sensors, limited computing power and limited energy are deployed to monitor an environment [26][27]. Typically, WSN has little or no infrastructure. WSN is a vibrant field attracting researchers and engineers due to its low cost and size [28]. It is believed by many that WSN will soon become more important than the internet itself. As such, the speed at which new technologies in this field are developed is overwhelming. Therefore, it is necessary to bring the reader up to speed on state of the art techniques and devices developed so far.

WSN finds application in many fields, some of these fields are: monitoring change in the ecosystem, battle field surveillance, monitoring patients remotely, industrial sensing and automation [29][30]. Wireless sensor network is also used in tracking assets, animals and humans. Furthermore, OGI also adopt the use of WSN in many of its sub-fields. Applications such as gas leakage detection, vehicle tracking, oil rig monitoring are but few of its applications.

Figure 2.1 shows the architecture of a typical sensor node. It consists of a power supply which is usually a battery or super capacitor. The system also consists of a *Microcontroller* which sometimes is replaced with a microprocessor or Field Programmable Gate Array (FPGA) [31] [32]. The main aim of this component is managing other components, on-board data processing and/or data aggregation and power management. The microcontroller unit usually runs on an operating system designed to manage sensor node's resources. Example of such operating

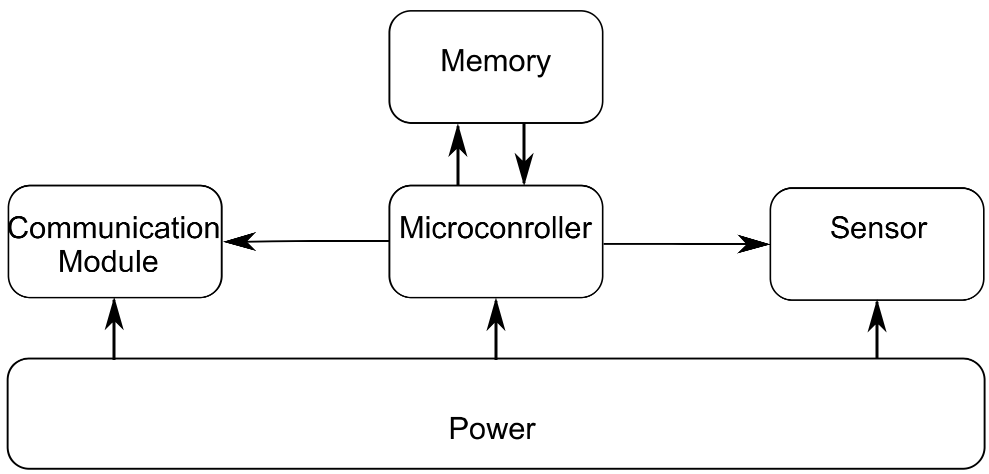

Figure 2.1: Architecture of a typical sensor node.

systems are *TinyOS*[33] and *Contiki* [34], and *LiteOS* [35]. This processing unit has a supporting *Flash memory* and *Random Access Memory (RAM)*, both of which have limited size (in the range of kilobytes). They are used to store operating system and other predefined information needed [29]. The *Communication system* also known as the "*Radio*", is responsible for the node's wireless communication with other nodes. It is the main culprit for energy consumption in WSN. It's energy consumption ranges from 15-300mW with transmission and idle listening consuming the most energy [36]. In addition, the range of transmission is in tens of meters, usually 10m to 20m [37]. Finally, the *Sensor* depends on the application. Some consume little energy like the temperature sensor, microphones and light sensors. While others like gas sensors consume as much (if not more) energy than the radio itself.

2.2.1 Different Implementations of WSN

The need for WSNs cannot be over emphasized, as such there is need for standardization. The standard is compartmentalized into layers. These layers form what is known as "*Stack*", which can be seen in Figure 2.2. Furthermore, each layer provides service to-and-only-to the layer above it, while a layer can only receive service from layer below it. The IEEE 802.15.4[38] is the widely accepted standard for the physical (PHY) and Medium access (MAC) layer for Wireless Personal Area Network (WPAN) which is used in sensing, monitoring and control systems [39]. A consortium of companies, later known as Zigbee Alliance add other layers such as security, routing and application layer. Thereby making it a complete system.

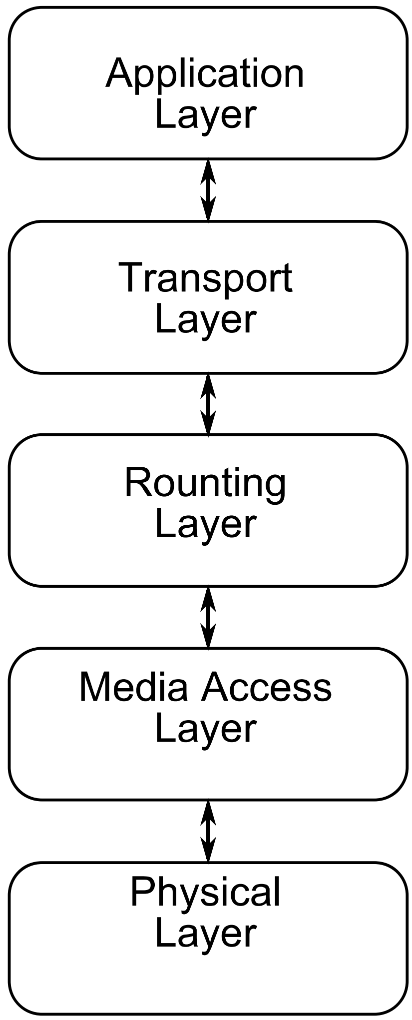

Figure 2.2: Wireless Sensor Network stack [36].

The Application layer is found at the top of the stack. It is responsible for carrying out the sensing and other interactions to the outside world. This layer provides services to the user. It should be noted that the term "*User*" can be anything that utilizes the services provided by the application layer. Therefore, the user can be a human, another node or a machine. The application layer determines the node type [40]. IEEE 802.15.4 specifies that a WPAN must have two types of node; Reduce Function Device (RFD) and Full Function Device (FFD). A network must also have atleast one of the FFDs as a network coordinator and the RFDs can have other functions ranging from sensing to routing data.

Once the application layer gathers information from the user it is then send to the *Transport* Layer. In WSN data needs to move from the sensor nodes (RFD) to the sink (FFD). The transport layer is responsible for ensuring end-to-end transmission and it is also responsible for managing congestion in the network.

Routing layer, also known as Network layer, it is responsible for hop-to-hop data forwarding. It is also responsible for determining the optimal path for data transmission.

The MAC layer provides access to the PHY layer and is also is responsible for synchronization and successful and reliable link with the MAC from the receiving node.

The *Physical (PHY)* layer is responsible for converting bits into electromagnetic waves which are then transmitted to a receiver. The receiver's PHY layer then converts the EM signal into bits that are then forwarded to the MAC layer.

Table 2.1: Comparison of Zigbee PRO, WirelessHART and ISA100.11a [45].

Feature Set	Zig bee PRO	WirelessHART	ISAlOO.l1a
Topology	Mesh	Mesh,Star, Combined	Mesh, Star, Combined
RF Channel	CSMA-CD	TDMA	TDMA/CSMA
Change	Yes	Yes	Yes
High Security	Yes	Yes	Yes
Keys	Symmetric	Symmetric	Symmetric/ Asymmetric
Interface Control/ Noise	Yes	Yes	Yes
Energy Saving	Yes	Yes	Yes
Interoperability to other systems systems	Yes	Yes	Yes
Application Context	Commercial	Industrial	Industrial
Reliability Determinism	No	Yes	Yes
Latency determinism	No	Yes	Yes
Implementation	Easy	Challenging	Challenging

As mentioned earlier IEEE 802.15.4 provides specification for the PHY and the MAC layer only. Other higher layers are provided by wireless technology companies. For example, Cisco, Digi, Ember, Emerson, Free scale, Honeywell, Intel, Itron, Kroger, Philips, Reliant Energy, Siemens, Sony, Texas Instruments form what is known as Zigbee Alliance [41]. Zigbee Alliance developed the *Zigbee PRO* protocol [42]. Other notable protocols are the *WirelessHART* [43] and *ISA100.11a* [44]. Table 2.1 compares the three well known protocols in WSN [45]. Further discussion will on focus on Zigbee alone, for the other two are beyond the scope of this report.

ZigBee

In August of 2001, Zigbee Alliance published the Zigbee specifiation [46]. It is an Implementation of WSN having Application-, Network- and Security layer on top of the MAC and PHY layer specified by 1EEE 802.15.4. The system has the following specification [46]:

1. Zigbee operates in the ISM band (i.e. 2.4GHz). It also uses 868MHz and 915MHz in Europe and America respectively.

2. It allows for star and mesh topology.

3. It has discovery and pairing mechanism.

4. It also Utilizes AES-128 security scheme.

5. It support standard both standard and custom application profiles.

Figure 2.3 shows a typical Zigbee network. Zigbee consist of three types of device in the application layer; *Coordinator-*, *Router-* and *End Node*. The first is a FFD while the remaining are RFDs. There should be one coordinator in a network. It is responsible for the initiating, securing and managing the network. Coordinators are not allowed to go to sleep. Although the idea of using only one coordinator provides centralization, it also provides single point of failure.

The router on the other hand is responsible for the forwarding of packets from an end node to the coordinator in a multi-hop fashion. It should be noted that Zigbee also allows for broadcast of data. In addition, the router is also not allowed to go to sleep.

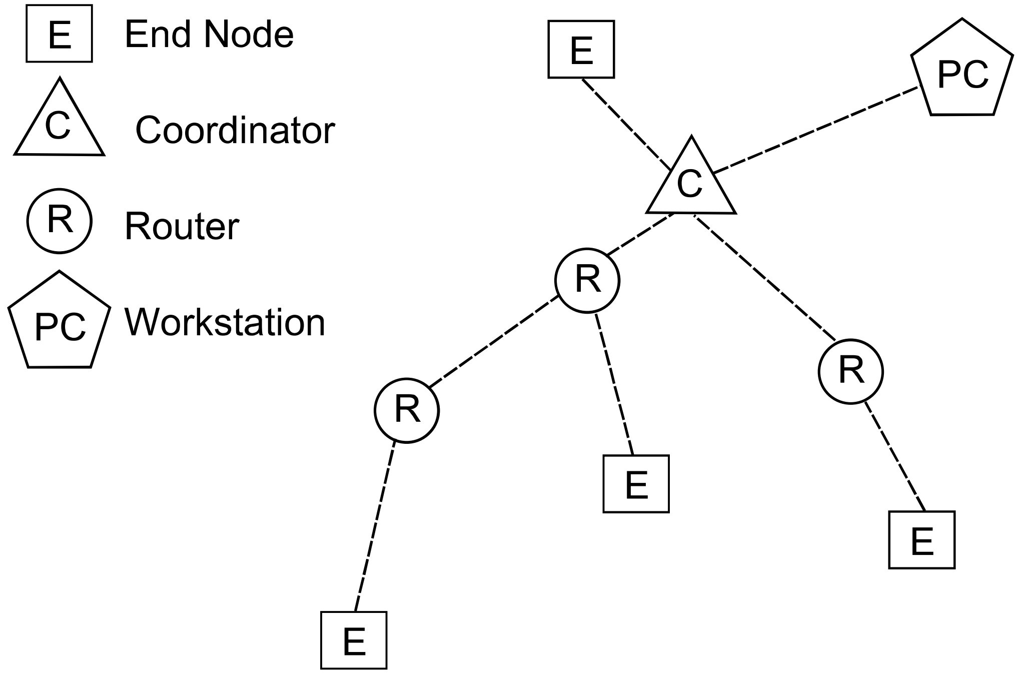

Figure 2.3: An implementation of Zigbee Network.

Finally, the End node is another RFD that is used mainly for sensing the environment. The End nodes are allowed to sleep and new nodes can be allowed to join the network depending on the application. Zigbee allows upto 64,000 nodes to join a single network and it can support up to 240 end nodes having different application but sharing the same radio [46].

2.2.2 WSN in Oil and Gas Industry

The recent embrace of WSN in OGI and manufacturing industries can be attributed to it's simplicity in installation and maintenance, low power consumption and low cost. WSN is applied in many aspects of OGI. It is applied in tracking products and vehicle in the form of Radio-Frequency Identification (RFID) system [14]. Carlsen *et al.* [47] reported how WSN can be used in environmental sensing in order to prevent loss of oil production at an offshore facility. It also find application in monitoring and maintenance of machines.

WSN requirement in OGI

The OGI is an area that have special requirements compared to most of its counterparts. Implementations of new technology must have low failure rate, because failure in OGI spells catastrophe to the workers, the company and the environment. Petersen *et al* [48][14], brought forward the following requirements ;

1. Frequency spectrum should be within the ISM (2.4GHz) band and its standards should be open in order to encourage compatibility and development.

2. Long battery life is also very important.

3. The system should be able to co-exist with other wireless system installed nearby.

4. It should be secured and its performance should be quantifiable.

2.2.3 Challenges to WSN in OGI

One of the biggest challenges is educating the potential consumers in the OGI on the potentials of WSN to solve their problem. Deployment of WSN offshore faces *Faraday cage* effect, thereby preventing signal to pass from one location to another easily [48]. Another challenge to WSN in OGI is it's compatibility with existing systems. Most of OGI solutions use middlewares that are too complex for the sensor nodes processing [49]. Furthermore, [50] pointed out that while most conventional middlewares work on the application layer, it is virtually impossible to separate WSN's application layer from its network layer without impairing performance.

Another serious challenge is that new areas of technology tend to over look human factor when designing systems [49][48]. OGI is a dynamic industry, as such WSN systems already installed should be easily integrated with new systems and vice versa. It is found that the need to replace or change existing system before installation of new (WSN) systems is one of the core reasons why certain WSN implementations are rejected.

2.3 Toxic and Combustible Gases

There is more gas in the soil than it actually seems. Bunnell *et al.* [51] reported that 25% of soil composition is made up of gases. This led to the term *Soil Atmosphere*. Bremner *et al.* [52], define soil atmosphere as "the gaseous phase of the soil, being that volume not occupied by solid or liquid". These *Underground Gases* originate from the atmosphere, decay of organic matter, geochemical reactions and thermal decomposition of organic and inorganic compounds. Although these gases are mostly found in small quantity, they can be found in large quantity if certain geologic conditions warrant and they could escape while drilling. Thereby causing fire disaster, toxic or corrosive atmosphere.

In this section provides and introductory information on toxic and combustible underground gases [53]. However, discussions in this section are confined to Methane, Carbon-monoxide and Hydrogen Sulfide, since our research is more interested in them.

2.3.1 Methane

Although scientists disagree over how methane is formed, the popular theory is that methane is formed as a result anaerobic decomposition of organic materials by bacteria known as *Methanogenic* bacteria[54][55]. Methane is the major constituent (70%-95%) of natural gas [56]. Methane combustion is more efficient than other fossil fuels. It also produce less carbon dioxide. It produce less toxic waste when used for electric energy production compared to coal and it is in abundance.

Kotz *et al.* report that an estimate of $1.5 \times 10^{13} tons$ of methane is is buried under the sea floor around the world in the form of *Methane Hydrate*.

However, methane is a green house gas, just like carbon dioxide. In addition, it destroys the the ozone layer, which is found in the upper atmosphere which protects us from solar radiation. Some of the techniques used in obtaining methane from the underground (such as *Fracking*) are not environment friendly. Transportation and storage of natural gases is also expensive.

Physical properties of Methane

Some of the physical properties of Methane are;

1. Methane is colourless.
2. It is odour less.
3. It has a melting point of 183^oC and a boiling point of 161.5^oC
4. It has a density of $0.66kg/m^3$ (lighter than air) at STP.
5. It is soluble in water.

Chemical properties of Methane

Methane, also represented by the chemical formula CH_4 consists of a carbon atom in weak covalent bond with four hydrogen atoms. Other chemical properties of Methane are;

1. Methane is combustible, when it completely burns in oxygen it produce carbon dioxide and water.

2. It reacts with halogens in a process called *Halogenation*.

3. Methane is a weak acid.

Methane is not toxic but it is highly flammable. It burns at a temperature of $(900 - 1500^oC)$ with blue flame and no smoke, making it the most efficient fossil fuel known so far.

2.3.2 Carbon monoxide

Carbon monoxide is one of the most notorious inorganic pollutants. Bulk of carbon monoxide production is due to human activity, largely due to combustion of carbonaceous materials when used as fuel or industrial processes [57]. Carbon monoxide is naturally formed during oxidation of methane during the decay of plants [55]. Carbon monoxide is not found in large quantities deep underground, albeit sparse quantity is found in underground coal mines and in volcanic and mash gases [58].

Carbon monoxide is poisonous. When in healed it combines with red blood cell's hemoglobin to form *Carboxyhemoglobin*. This compound has a stronger bond than *Oxyhemoglobin* — a compound that helps transport oxygen to the different part of the body. Hence preventing oxygenation of blood [59]. Table 2.2 shows the effect of carbon monoxide on the body.

Table 2.2: Effect of Carbon Monoxide [59].

Effect	Concentration (%)
Normal presence of carboxyhemoglobin in blood	0.5–0.8
Patients with cardiovascular disease get impaired cardiovascular function	3–5
Carboxyhemoglobin in smokers blood	3–10
Slight headache	10–20
Impaired visual function	>20
Coma accompanied with intermittent convulsions	50–60
Death	70–80

However, Carbon monoxide has some applications: it is used in coloring meat to make look fresh, it is used alongside other chemicals to forms anti-inflammatories and vasodilators, it is also used as a lasing medium in high power laser and it is used in production of iron and steel.

Physical properties of Carbon monoxide

The following are some physical properties of carbon monoxide;

1. Carbon monoxide is colorless.
2. It is odourless.
3. It has a density of $1.250kg/m^3$ (slightly less dense than air).
4. It has a melting point 205.02^oC and a boiling point 191.5^oC.
5. it is soluble in acetic acid, ammonium hydroxide, benzene, chloroform, ethyl acetate, ethanol and water.

Chemical properties of Carbon monoxide

CO is the molecular formula of carbon monoxide. The structure consists of a carbon atom in two covalent bond and a single dative covalent bond the an oxygen atom. Other chemical properties of carbon monoxide are;

1. It burns in the presence of oxygen to form carbon dioxide (CO_2).

2. It reacts with water to form carbon dioxide and hydrogen gas.

3. It reacts with nitrogen dioxide to from carbon dioxide and nitrogen(II)oxide.

2.3.3 Hydrogen Sulfide

Hydrogen sulfide is another important gas in the atmosphere where sulfur is in lower oxidation state — further oxidation in the atmosphere produces sulfate and sulfur dioxide. It naturally occurs as a result of microbial processes such as sulfur based compound degradation and sulfate reduction by bacteria [60]. Hydrogen sulfide can be found in petroleum, natural gas and geothermal steam [61].

Although Hydrogen sulfide is a very dangerous gas (see also: Table 2.3 [62]), it has many useful applications; hydrogen sulfide reacts with alcohols to form thiols. This is a smelly group of organosulfur compounds that are used in adding smell to cooking gas. Hydrogen Sulfide is also produced in minute quantities in the body of mammals as a signaling molecules. Hydrogen Sulfide also helps in tissue repair and resolution of inflammation [63]. It also help rescue organs in heart related (a.k.a vascular) diseases [64]. It also helps prevent build up of *Plaque* inside the

Table 2.3: Effect of Hydrogen Sulfide [62].

Effect	Concentration (*ppm*)
Odor Threshold	0.003–0.02
Rotten egg odor	Up to 30
Sickly sweet odor	30–100
Olfactory fatigue	>100
Eye irritation, corneal erosion, conjunctivitis	<20ppm/<8 hours
Burning of the eyes, headache, shortness of breath, dizzines , weight loss, loss of appetite	15–25
Acute conjunctivitis, pain, lachrymation, photophobia, keratoconjunctivitis	50ppm/1 hour
Loss of consciousness, arm cramps, low blood pressure	230ppm / 20min
Unconsciousness, low blood pressure, pulmonary edema, convulsions, hematuria, death	>1000pp/>1min
Coma after single breath	1000–2000
Pulmonary edema	250, prolonged exposure

arteries [65]. Plaque is a material made up of fat, cholesterol, calcium, and other substances found in the blood.

Physical properties of Hydrogen Sulfide

Hydrogen Sulfide is in gaseous form at STP. Although it has a pungent smell, it is dangerous for one to trust ones sense of smell, because long exposure to even minute quantity can cause the olfactory fatigue rendering ones sense of smell numb. Therefore, it is recommended for those working areas with the risk of hydrogen sulfide leakage to always be at the mercy of a portable toxic gas detector.

1. Hydrogen Sulfide is colorless with rotten egg smell.

2. It is also soluble in water, thereby forming *Hydrosulfuric* acid or *Sulfhydric* acid.

3. It has also has a melting point 82^oC and boiling point 60^oC.

4. It has a density of $1.363gdm^3$, making it slightly heavier than air.

Chemical properties of Hydrogen sulfide

Some of the chemical characteristics of hydrogen sulfide are;

1. Hydrogen Sulfide (H_2S) is consists of two covalent bond with hydrogen atoms at 92.1^o apart.

2. Hydrogen sulfide burns in oxygen with a blue flame to produce sulfur dioxide (SO_2) and water.

3. Hydrogen sulfide is a reducing agent.

4. Gaseous hydrogen sulfide explodes when it comes in contact with concentrated nitric acid.

2.4 Toxic and Combustible Gas Sensors

Gas concentration is measured in *Parts Per Million* (ppm) which is the ratio of volume of gas (in micro Liters) to that of air (in Liters) (see also: Equation 2.1 and 2.2). Allowable gas concentrations in a working environment are enforced by government agencies. Some of these agencies are; *American Conference of Governmental Industrial Hygienists (ACGIH)* and *Occupational Safety and Health Administration (OSHA)*. Both are American agencies. They enforce allowable-gas-concentration laws based on the flammability or toxicity of the given gas.

$$Concentration(ppm) = \frac{Volume \quad of \quad gas \quad or \quad Vapor(\mu L)}{Volume \quad of \quad air(L)} \tag{2.1}$$

$$Concentration(ppm) = \frac{V_m}{M} \times \frac{mass \quad of \quad gas(\mu g}{Volume \quad of \quad air(L)} \tag{2.2}$$

Where:

V_m = standard molar volume of ideal gas (at 1 bar and 273.15 K)[22.71108 L/mol] [66]

M = molecular weight of gas [g/mol]

Flammability is percentage volume of gas or vapor mixed in air and it is categorized in to: *Lower Exposure Limit (LEL)* and *Upper Exposure Limit (UEL)*. LEL is the level below which combustion cannot take place even when the mixture (of air and gas or vapor) is in contact with an ignition source. UEL on the other hand, is the maximum percentage volume of mixture of a gas or vapor with air that will start combustion when in contact with ignition source. Table 2.4 shows the LEL and UEL of some selected gases [67][68].

Table 2.4: Approximate LEL, UEL and TLV of some gases at Standard Temperature and Pressure (STP) [67][68].

Gas	LEL (vol%)	UEL (vol%)	TLV (ppm)
Methane	5.3	15	-
Carbon monoxide	12.5	74	50
Hydrogen Sulfide	4.3	45.5	10
Hydrogen	4.0	75	-
Ethane	3.0	12.5	-
Propane	2.2	9.5	1000
N-butane	1.9	8.5	-
Natural gas	4.8	13.5	-

Toxicity on the other hand, is the degree to which an organism can be damaged by a given substance. Toxic gases are measured in a different manner than combustible ones. Since time is a crucial factor in determining exposure limit to such gases, *Threshold Limit Values (TLVs)* are enforced by government agencies mentioned earlier. There are three TLVs and these are; *Time Weighted Average (TWA)*, *Short-Term Exposure Limit (STEL)* and *Ceiling Limit (CL)*. TWA is the average concentration level all workers are allowed to be exposed to for about 8 hours a day and 40 hours a week without any adverse effect. Table 2.4 shows TLV-TWA of some toxic OGI related gases. STEL is a time-weighted average concentration level worker are allowed to be exposed to for a short period of time (15min or less). To calculate STEL, Equation 2.3 is used along with Table 2.5 [69]. For example Carbon monoxide has a TLV of 50ppm, therefore its STEL is 75ppm ($50.5 = 75ppm$). Finally, *Ceiling Limit (CL)* is the concentration that must not be exceed in any case.

$$STEL(ppm) = TLV \times Excursion \quad Factor \tag{2.3}$$

Table 2.5: TLV of some selected gases [69].

TLV(ppm or mg/m^3)	Excursion Factor
0–1	3
1–10	2
10–100	1.5
100–1000	1.25

Gas sensors can be classified base on the the type of gas they sense (see also: Figure 2.5), sensing material or base on the type of output that indicates the gas concentration in the atmosphere. In this section we are only interested in toxic and combustible gas sensors, for more information on gas sensor please refer to [70][71][72].

2.4.1 Catalytic Sensors

Catalytic Sensors are also known as *Catalytic Beads* sensors are one of the early gas sensors that replace canaries [73][74]. They work base on the principle of catalytic combustion, where gases oxidize (burn) at low temperatures with the help of a catalyst. A catalytic bead is made up of platinum wire coil covered by alumina bead which is encased in a catalyst as shown in Figure 2.4. The catalyst depends on the gas to be sensed.

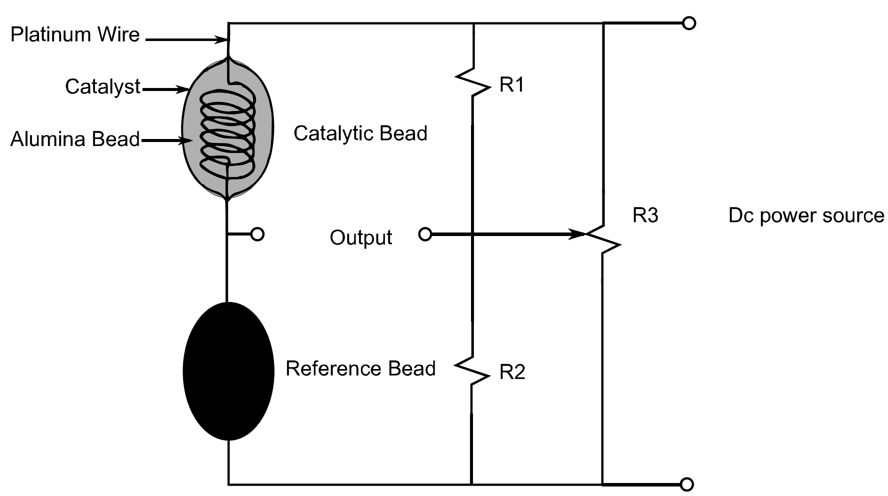

Figure 2.4: Catatlytic bead sensor (extracted from www.e-ucenje-kel.ftn.uns.ac.rs).

In order to ensure accurate results, the circuit in Figure 2.4 is recommended [73]. Catalytic bead sensors are notorious for their ruggedness, small size and long life. However, catalytic poisoning due to reaction with some compounds

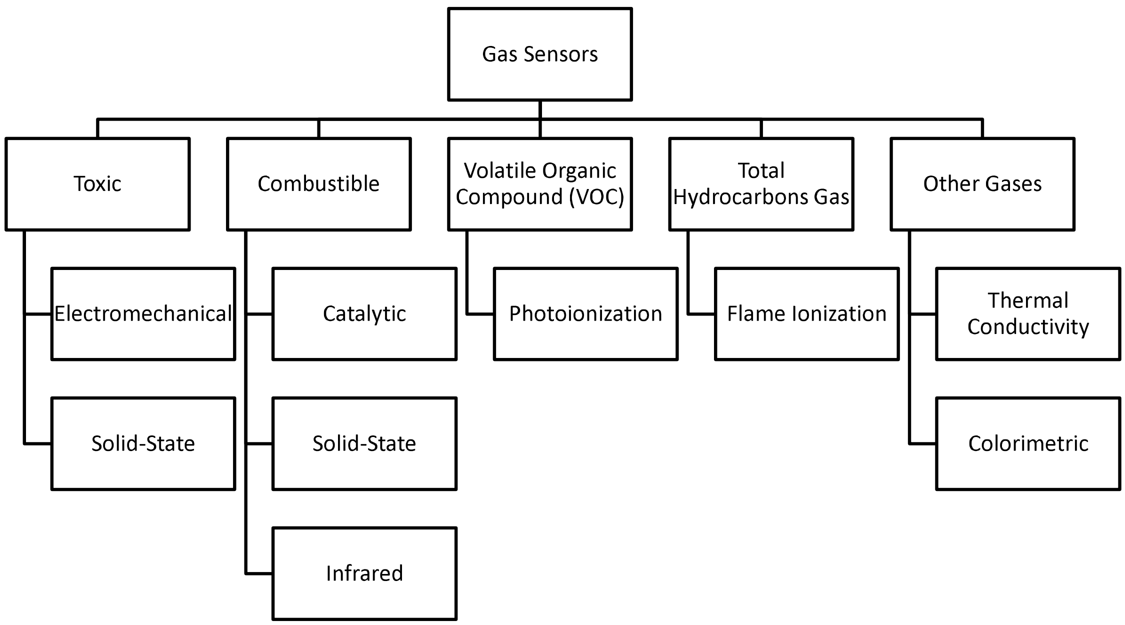

Figure 2.5: A tree diagram of the different types of Gas Sensors base on the gas they sense.

and sensor cracking permanently reduce the performance of this type of sensor. Presence of sensor inhibitors can also temporarily impair the sensors accuracy. These are some of the drawbacks of gas sensors.

2.4.2 Infrared Sensors

Figure 2.6 shows a typical infrared gas sensor. An infrared gas sensor as the name implies uses an infrared source and an infrared sensor. In between is the target gas which is allowed to pass through the inlet and exit through the outlet. In presence of the target gas, energy is transferred from the infrared light to the target gas. This energy absorption is described by Beer-Lambert Law shown in Equation 2.4 [75].

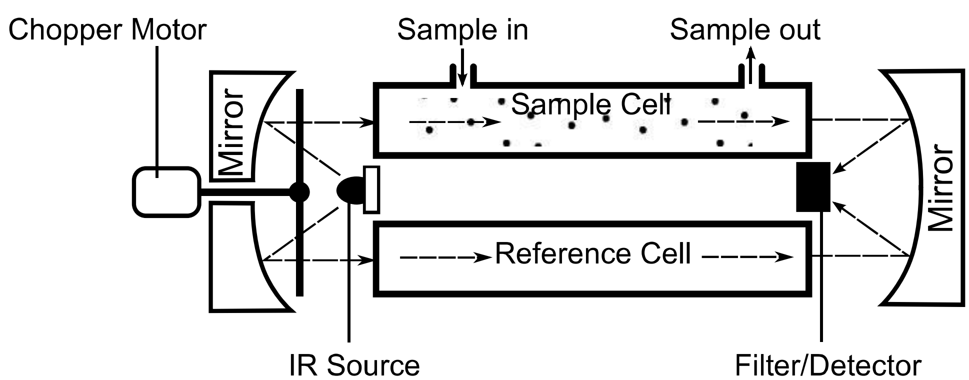

Figure 2.6: Infrared Sensor (Extracted from www.rkiinstruments.com).

$$I = I_0 e^{-\alpha ct} \tag{2.4}$$

Where

I = Intensity of beam at the receiving end.

I_0 = Intensity of incident beam.

α = Molar extinction, which is dependent on both molecule of target gas and wavelength of incident light.

t = distance traveled by the light.

As the gases absorb the energy they vibrate faster and their temperature rises. An array of infrared sensors measure the deviations from the original state of the system. There are three notable types of infrared gas sensor: 1) *LUFT* infrared sensors (see also: Figure 2.6), which measure the amount of light absorbed by the target gas. 2) *Pyroelectric* infrared sensors measure the change in temperature of the gas. 3) *Photoacoustc* sensors measure the pressure change using a condenser microphone.

Infrared gas sensor is notable for its none destructive method of measurement, in that the sensed gas is not engaged in any chemical reaction. All the sensor's components are protected from the gas therefore there is no possibility of sensor being damaged by poisoning or high concentration of the target gas. As the sensor ages the sensor components degrade, but since there is only one light source and sink is used, no re-calibration is needed. The infrared sensor also has some drawbacks: it is expensive, it cannot measure certain gases that do not absorb infrared energy (for example hydrogen), its accuracy falls in the presence of multiple gases and it is harder to maintain in humid and dusty environments.

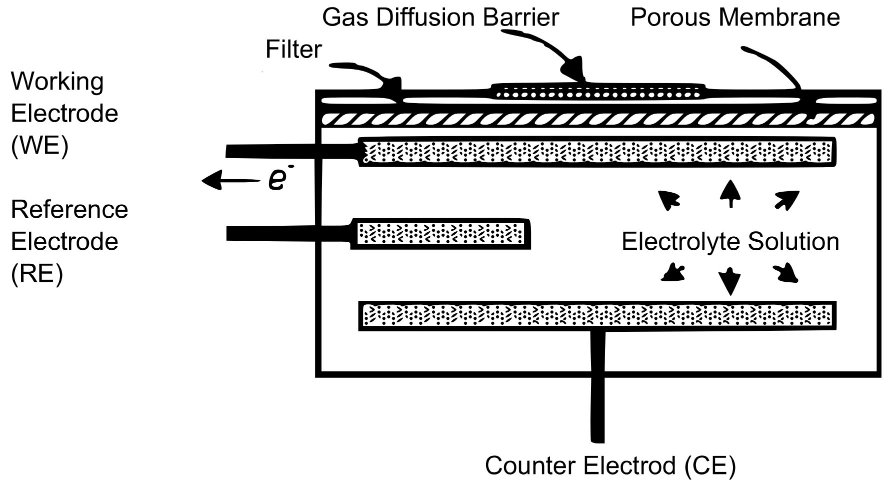

Figure 2.7: Electrochemical Sensor (Extracted from www.electronicdesign.com).

2.4.3 Electrochemical Sensor

Electrochemical sensors as the name implies are devices that sense the presence of gases through the used of a fuel cell shown in Figure 2.7. The system consists of three electrodes; Working electrode, Reference electrode and Counter electrode. As can be seen from Equation 2.5, 2.6 and 2.7, chemical reaction liberating electrons takes place when the working electrode come in contact with the targeted gas (CO in the case of Equation 2.5) . The electrons travel through the electrolyte from the anode (working electrode) to the cathode (i.e counter electrode). The electrons are absorbed and water is formed. The movement of electrons from the anode to the cathode generates current. Furthermore, the more the targeted gas diffuses in the electrolyte the more electrons liberated, hence the more current produced. As such the current produced is proportional to the gas in the atmosphere [76]. Since the gases react with the surface of the working electrode, the performance of the sensor deteriorates with time. This is why a reference electrode is added. The current is not allowed to pass through the reference electrode, hence it does not suffer any deformation due to chemical reactions that take place in the cell. Scrubber filters are used to stop unwanted gases from reaching the electrolyte [77].

$$\text{Working Electrode:} \qquad CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^- \tag{2.5}$$

$$\text{Counter Electrode:} \qquad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2.6}$$

$$\text{Overall reaction:} \qquad 2CO + O_2 \rightarrow 2CO_2 \tag{2.7}$$

Electrochemical sensors are not easily poisoned, they are also light, the are energy efficient since they do not require any external source of energy and they are very accurate. However, they have shorter life span compared to other combustible and toxic gas sensors, they operate over a narrow temperature range and their performance is interfered by gases such as hydrogen.

2.4.4 Semiconductor Sensors

Semiconductor sensors are also referred to as *Solid-state* or *Metal Oxide* sensors. They work base on the principle that certain gases alter the normal performance of solid state devices. For example, the resistance of n-type semiconductors (usually doped with Tin oxide (SnO_2)) decreases upon contact with a reducing agent and increases when it comes in contact with an oxidizing one. P-type semiconductors (usually doped with Copper(II)oxide (CuO)) have the opposite response [78].

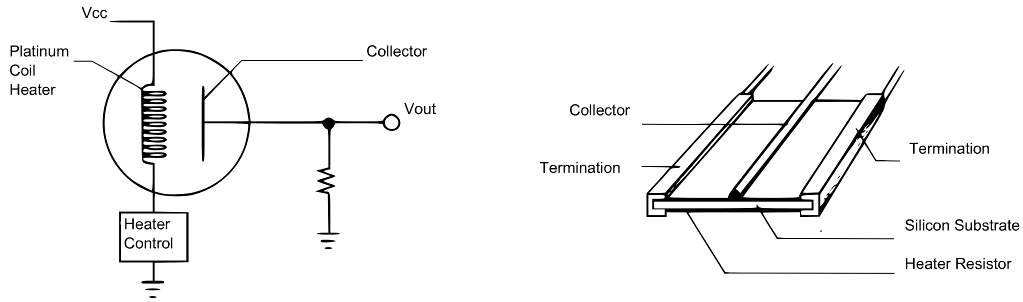

Figure 2.8: Bead type (left) and Chip type (right) semiconductor gas sensor (Extracted from intlsensor.com).

Semiconductor sensors are usually used to sense toxic gases, but are sometimes used in sensing combustible gases too. Figure 2.8 shows the two type of semiconductor gas sensors. Typically, the sensor has a heating element which could be made up of platinum coil, a resistive metal oxide, or a thin layer of deposited platinum. The heater heats the semiconductor to a temperature of $100^oC - 500^oC$ [79]. At this temperature the silicon substrate absorbs oxygen in the absence of the targeted gas as shown in Equation 2.8 and 2.9. The absorption of oxygen causes electron depletion, which leads to reduction in conductivity.

$$O_2(gas) + e^- \rightarrow O_2(ads)^- \tag{2.8}$$

$$O_2(gas)^- + e^- \rightarrow 2O(ads)^- \tag{2.9}$$

$$H_2S + 3O(ads)^- \rightarrow H_2O(g) + SO_2(g) + 3e^- \tag{2.10}$$

However, in the presence of the targeted gas, say hydrogen sulfide, the absorbed oxygen reacts with it. Equation 2.10 shows how H_2S reacts with the absorbed oxygen to form sulfur oxide gas, water vapor and free electrons. Hence increasing the conductivity of the substrate. In order to create different gas sensor, slight modifications are made to the substrate. Semiconductor sensors are good for detecting low ppm levels of gases, as well as high levels of combustible ones. They are also robust with a life expectancy of atleast 10 years [53]. They are also flexible in that the same gas sensor can measure toxic and combustible gas, they operate in wide range of temperature and humidity [80]. On the downside, huge energy consumption and false alarm are some of the sensor's drawbacks.

In this research, gas sensing is carried out by MQ-4, MQ-7 and MQ-136 semiconductor sensors for Methane, Carbon monoxide and Hydrogen sulfide respectively . These gases are selected because of their fatal consequence when they leaked. Yayavaram *et al.* [81] reported that semiconductor sensors readings in general follow the power law as shown by Equation 2.11.

$$R = K \times C^{\pm n} \tag{2.11}$$

$$R = \frac{R_s}{R_0} \tag{2.12}$$

Where

R = Electrical resistance of the sensor

K = measurement constant of the sensor material

C = Concentration of the target gas in ppm

n=sensitivity index of the material (between 0.3-0.8)

2.5 Actuators

An actuator in piping design is any device connected to a valve that moves the sealing element of the valve [82]. In Electrical Engineering however, an actuator is any device that can convert electrical energy into mechanical energy. *Solenoid Valves, Electric Valve Actuators* are discussed in this section. For further information on valves and actuators refer to [82] [83].

2.5.1 Solenoid Valves

A Valve controls the flow of fluid. It is worth noting that modern valves in addition to flow control can also control flow rate, pressure and/or direction [84]. Some valves have built-in digital control and communication systems in order to ensure high performance, such valves are called "*Smart Valves*" [82] [85]. Figure 2.9 shows a solenoid valve. The solenoid coil is magnetized as current passes through it thus lifting the soft iron core. Once the iron core is lifted the valve is opened and fluid can pass through the valve. The solenoid loses its magnetism when the current is no longer passing through it. This causes the spring to push the valve downwards, closing the valve and stopping the flow of fluid through it.

Solenoid valves are easy to operate, install and maintain. They can operate in either AC or DC. However, solenoid valves have some drawbacks, one of which is high power rating ranging from 30VARMS-300VARMS and 18W-30W for AC and DC respectively [86] [87] [88]. The huge energy consumption is due to the coils. Another drawback of solenoid valves is the back EMF produced by the coils which

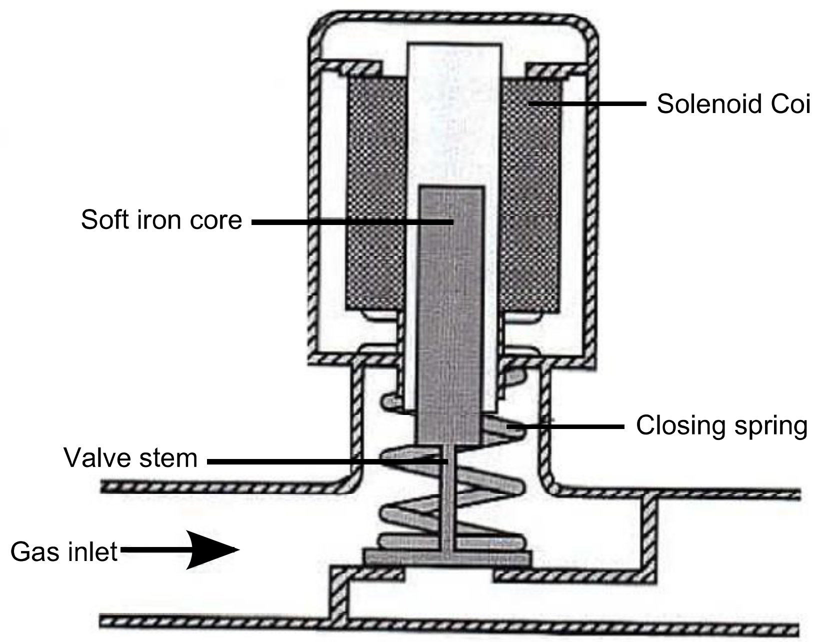

Figure 2.9: A diagram of Solenoid Valve courtesy of upperplumber.co.uk.

oppose the voltage applied across the coil by the user. To solve this problem a diode in reverse bias to the applied voltage is placed across the coil.

2.5.2 Electronic Valve Actuators

In order to distinguish between devices that convert electrical energy to mechanical and devices that open and close valves. The earlier are called *Actuators* while the later are called *Valve Actuators*. Valve actuators can be classified according to their source of energy: Pneumatic actuator as the name implies are actuators that are powered by air, Hydraulic actuators are the most powerful and are powered by liquids while electric valve actuators use electricity to open or close valves.

Electric actuators can be classified into;

1. Solenoid Actuators

2. Motor Driven Actuators

The solenoid actuator use similar principle as the solenoid valve, it is attached to the valve stem which is responsible for opening and closing the valve. Hence, the magnetizing and demagnetizing effect of the solenoid causes the stem to move up and down thereby opening and closing the valve.

Motor driven actuators as the name implies, use electric motors connected to a system of gears which is connected to the valve stem. Figure 2.10 is an example of a motor driven actuator [89]. Obviously, this kind of actuator is used with rotary valves where rotational movement is needed to open and close the valve. Although electric parts of these kind of actuator are prone to damage by water, the

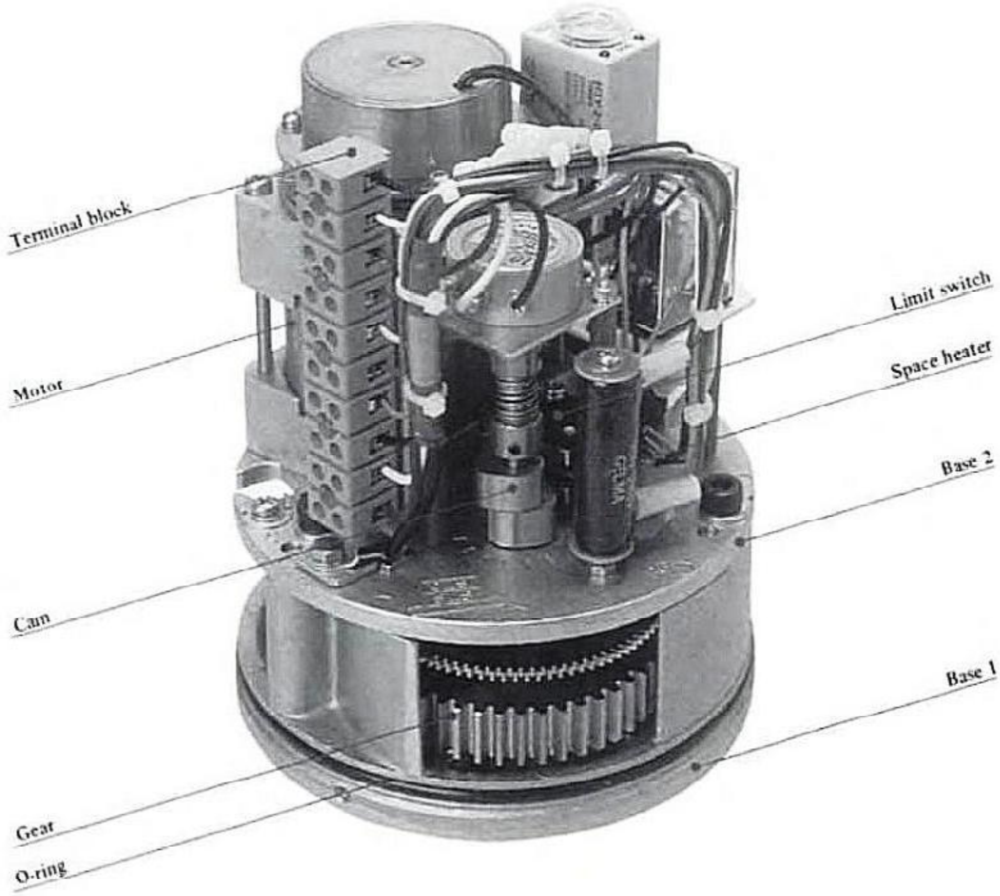

Figure 2.10: A diagram of Motor driven actuator.

are notorious for their resistance to harsh environment. Motor driven actuators also inherit the drawback of solenoid valve mention in Section 2.5.1.

2.6 Summary

This chapter has provided basic information on the key components of this project. The chapter has explain the physical and chemical behavior of the gases involved in the experiment. The research has further shown the danger of their use. Furthermore, actuators and valves were also presented.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

Engineers prefer wired systems to Wireless Gas Sensor Network (WGSN) [90] [91] base on the fact that they are reliable and they can provide abundant resources such as energy and bandwidth. However, wired systems have some drawbacks: their installation is costly in terms of time, money and manpower (all of which are not taken for granted in the Oil and Gas Industry); during relocation (e.g. in oil exploration), huge man power is needed to remove and transport the system to a new location where it will be installed again; finally, wired methods are impractical in some applications, for example in pipeline monitoring where network of pipelines span thousands of kilometers or more. Recent development in wireless technology has allowed for the reliable use of wireless communication in the noisy industrial environment. Zigbee (IEEE 802.15.4) is one of such developments certified for industrial sensing and diagnostic applications [92]. This pave the way for different kind of WGSN applications.

In this chapter, state of the art designs and research breakthroughs of other researchers in the WGSN are analyzed, in the hope of finding a perfect WGSN solution that complies with industrial standards. Our proposed solution is also briefly discussed.

3.2 Literature Review

Fraiwan *et al.* [93] proposed a gas leakage detection system consisting of gas *detection and transmission module* and a *receiver* module. The gas detection and transmission module is made up of a MQ-5 *Solid State* gas sensor which is capable of sensing Liquefied Petroleum Gas (LPG), Methane Carbon(II)oxide (CO) and Hydrogen gas (H_2). In addition, the gas detection module also consists of an alarm system and a *TXM-433-10* RF transmitter. The receiver module on the other hand, consists of an alarm system and a *SILRX-418* RF receiver. The system uses *PIC16F877A* as a processing device. The system uses simplex method of transmission (from the gas detection module to the receiver), which means users have limited or no control over it. The MQ5 sensor is not an accurate sensor give the fact that it is not designed and/or optimized for a particular gas [93]. As such this system cannot be used for industrial applications.

In order to increase processing power and flexibility of sensor nodes, [31] developed a WGSN using a LPC2148 arm7 microprocessor, a μC/OS-II Real-time Operating System (RTOS), a MRF24J40 Zigbee wireless transceiver and three

(Humidity, Temperature and Gas) sensors. However, despite the use of a high speed microprocessor and three sensors, no attempts were made by the authors to curve energy consumption of the system. Furthermore, the the use of a proprietary OS (μC/OS-II) has violated the requirements of Oil and Gas Industrial (OGI) applications as specified by [14]. Recently, [94] develop a similar system using ARM7-LPC2148 microprocessor, but exclude the proprietary operating system in order to cut down cost. The system which is designed for both domestic and industrial use consists of a weighing sensor, a MQ-6 gas sensor, a voice alert system and a GSM module. In the event of gas leakage the gas sensor sends the amount of gas in the atmosphere in the form of analogue signal to a microprocessor. The microprocessor turns on an extractor fan in an effort to suck out the dangerous gas, at the same time the system also sends a SMS to a cell phone warning whom it may concern about the leakage. In addition, the system has other added value functionality of automatically booking gas order as soon as signal is received form the weighing sensor that the weight of cylinder is less than or equal to 2kg. Although the system has done away the proprietary software, it still fail to conform to some of the industrial standards: the system fail to provide explosion proof casing; the authors also fail to provide energy aware system which will ensure prolong battery life time and finally; the system does not have a diagnostic system.

Somov *et al.* [90] developed an active WGSN that uses a wireless actuator (electronic valve) to avoid fire disaster in the event of gas leakage by remotely closing the gas source through the valve. The system consists of four different type of wireless nodes: first is the combustible gas *Sensor Node* which is made up of a semiconductor gas sensor, a microcontroller and a Zigbee transciever; second is the *Relay Node* made up of only a Zigbee transceiver and a Atmega168p microcontroller — the relay node's responsibility is to extend transmission range between the gas sensor and the sink (*Network Coordinator*) by relaying traffic between the two; the third is the Network coordinator consisting of a Zigbee module, a MTSMC-G-F4-IP GSM/GPRS modem (for transmitting alerts to very far locations through SMS) and a L2478 microcontroller, this node starts and oversees the operation of the network, it also serves as a bridge between the Zigbee network and a workstation used by the *Network Operator*; finally, a *Wireless Actuator* which contains of a Zigbee module, a power supply and an electronic valve is added to the network in order to allow the the gas sensor to remotely seat the valve in case of high methane concentration in the atmosphere. Although the use of Zigbee network and a low power consuming microcontroller has saved lots of energy, the system still has a low life span and the 2D semiconductor methane sensor is the culprit. In addition, semiconductor sensors have impaired accuracy in small quantity of methane. In order to increase the accuracy of the system, the semiconductor sensor is replaced with a more sensitive catalytic sensor in [95]. Since the catalytic sensor needs to be connected in pairs with another catalytic sensor in a wheatstone bridge configuration with some resistors [73], huge energy consumption is expected. To solve this problem the authors of [90] replaced the wheatstone bridge configuration with a catalytic sensor in series with a $20k\Omega$ resistor forming a potential divider. The authors save energy but lose accuracy in the process.

Finally, [96] developed a context adaptive gas sensor using semiconductor sensor, a Pyroelectric InfraRed (PIR) sensor and Jeennic J5148 wireless microcontroller (running Zigbee stack). The system is designed in such a way that the duty cycle of the sensor node is a function of availability of people, their location and the velocity of the leaking gas. Therefore, once the PIR senses the presence of people, it alert the microcontroller to adjusts rate of gas detection base on the activity of the person in the environment, which can be deduced from his location. Furthermore, the system uses early detection mechanism by inferring the gas level through the peak value of the reading without waiting for the sensor reading to reach steady state. This allow the system to achieve longer life span than the systems mentioned earlier.

In this document, we report the development of a novel WGSN system for industrial application. The system is developed especially for outdoor applications like oil exploration and gas transportation. The system uses three gas sensors (Methane, Carbon(II)Oxide and Hydrogen Sulfide), an Atmega328p micorcontroller and a Xbee (Zigbee wireless module). The microcontroller is responsible for controlling transmission of data across the network, while the Zigbee module sets up a mesh network of sensor nodes and relay nodes in order to ensure maximum system reliability and flexibility. The system also employs energy harvesting through solar panels and rechargeable batteries in order to ensure maximum network life time.

3.3 Summary

In this chapter, previous works in the field of WGSN are reviewed and it is found that the two most widely used gas sensors for this kind of system are; Semiconductor and Catalytic sensor. Research has also shown that the semiconductor sensor consumes less energy while the catalytic sensor is more accurate. Also, we learn that mircocontrollers are the optimal processing unit for WSN applications.

CHAPTER 4

DESIGN AND ANALYSIS

4.1 Introduction

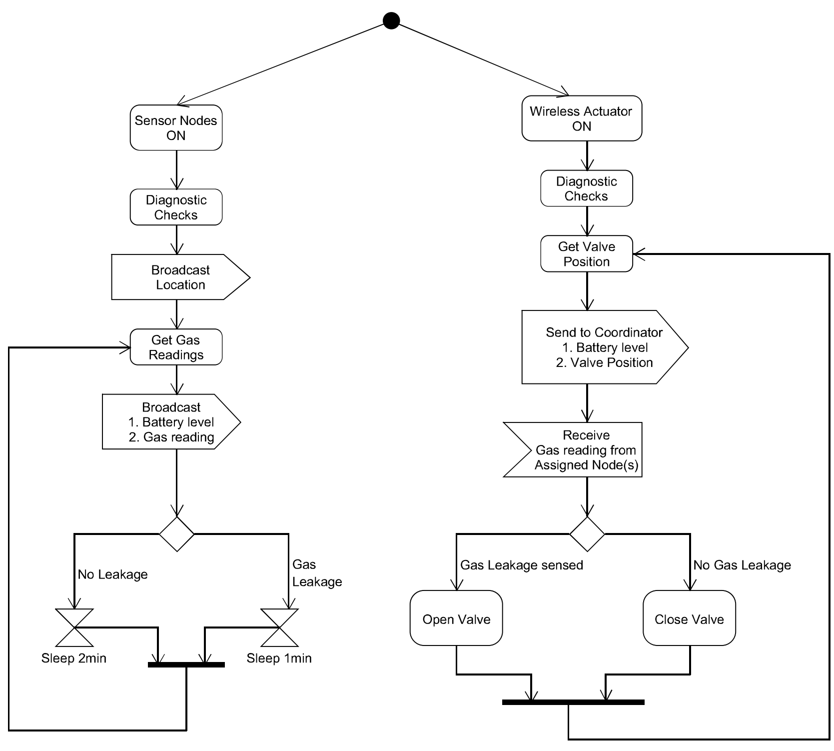

Figure 4.1: Top level Activity diagram for the proposed system.

Figure 4.1 provides a top level activity diagram of the system. The system has two key components; the sensor and the actuator. The sensor uses adaptive sleep cycles — when there is no leakage, the sensor sleeps longer (2min) and it sleeps less (1min) when there is gas leakage. Although the system goes to sleep during gas leakage the gas alarm stays on throughout the gas leakage incidence. Meanwhile, an actuator connected to a pipes listens to the gas readings broadcast and closes the valve when gas leakages is beyond a pre-programmed threshold or on the request of the coordinator.

In order to extend the coverage of the networks router nodes are used. Therefore a complete network may consist of a sensor, a router, an actuator and a coordinator.

In this chapter detailed information on the design and design analysis for the aforementioned system. The chapter explains how the system with the activity diagram in Figure 4.1 is designed. The system consists of both hardware and software components. Hence, this chapter is broken into two major sections where one explains the hardware design and the other explains software design.

4.2 Hardware Design and Analysis

This section presents the design of the sensor, actuator and relay node. The coordinator needs no extra circuitry because the Zigbee firmware installed in it fetches data from the Radio-Frequency (RF) buffer and loads it on the serial communication buffer. From there a Serial-to-USB converter is used to forward the packet to the computer through USB port. This circuit is not designed because it is readily available in the form of xBee-Explorer [97] or an Arduino board [98]. This saves us the time for designing another circuit and developing a USB-COM port driver.

4.2.1 Sensor Node

A sensor node has the role of sensing gas leakage and broadcasting the result. In other to successfully design a working sensor node,the node must have these basic functions:

1. The sensor node should be able to sense the targeted gases.
2. It should be able to convert the gas readings from raw analogue data to information readable by man.
3. It should be able to output the information through an output device, such that one can read it.
4. And it should be able to transmit/broadcast the information through wireless to the coordinator.

In other to achieve these functions, the block diagram shown in Figure 4.2 is developed. From the figure, one can see that a power supply unit is needed to power the whole system. There also has to a the gas sensing unit which is responsible for converting gas concentration in the atmosphere to commensurate voltage level. A mircocontroller is needed to convert the analogue signal to human readable format. The gas readings obtained are then display to users through a display. At the same time, the gas readings are passed to a wireless module for transmission. The design and selection of these basic components is as follows:

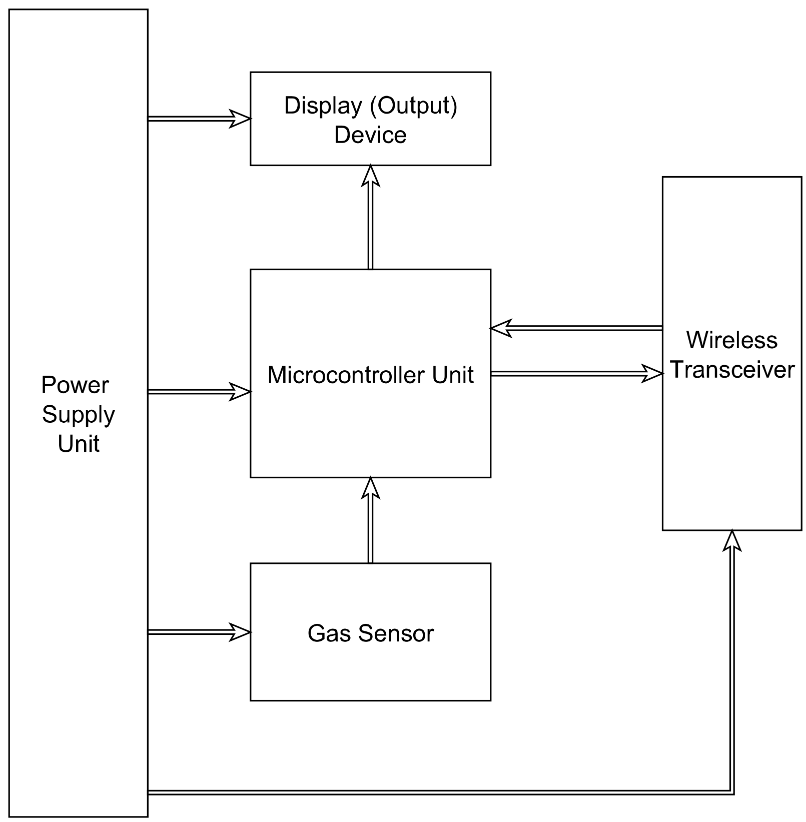

Figure 4.2: Basic components of the designed sensor node.

Display

The best technique for designing an electronic device is top down approach [99]. As such our design will start with the components that drive least number of other components in the system, to the does that drive the most.

The display (or output) device does not drive/provide any other device with output. Therefore the output device is our starting point. There are variety of output device one could use. One can use speakers, Light Emitting Diodes (LED) or Liquid Crystal Display (LCD). Since there is a lot of information to display (i.e. Battery level and Gas readings for three gases), then it is more logical to use LCD. This is due to the fact that an LCD can display the most volume of information while maintaining minimum energy consumption. The LCD can be connected as shown in Figure 4.3. In this configuration data, can be sent through the higher nibble of the data port [100]. This configuration has two benefits; 1) it reduces the number of MCU's ports used by the LCD is reduced thereby reducing the form factor of the entire circuit. 2) Source code driving this configuration is readily available. The maximum possible current for the LDC at +5v is (I_{LCD}) is the current consumed by the Liquid Crystal Display (LCD) is 3mA [101].

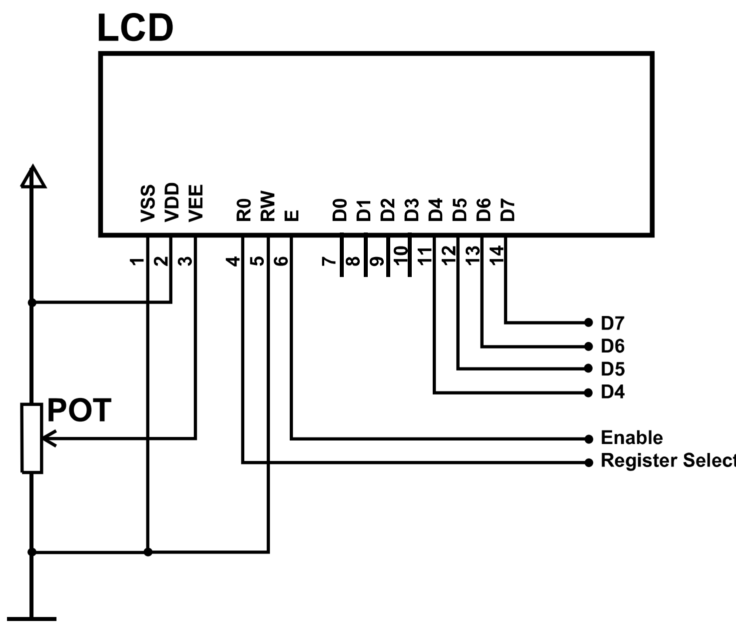

Figure 4.3: Setup for LCD.

GPS Device

EM-406A GPS receiver is used for localization [102]. This is accomplished when the MCU sends NMEA sentences to the GPS module commanding it to synchronize with the the GPS satellites [102]. This GPS receiver is the best choice because of its relatively small foot print and power consumption. The GPS transceiver is powered by +3.3v and consumes 44mA in acquisition mode [102]. The GPS device has no hibernate pin, hence power gating is applied using logic level transistor IRL520. The GPS device communicates with the microcontroller through serial communication (Universal Asynchronous Receiver/Transmitter [UART]). As such it is connected to the only serial port available on the microcontroller.

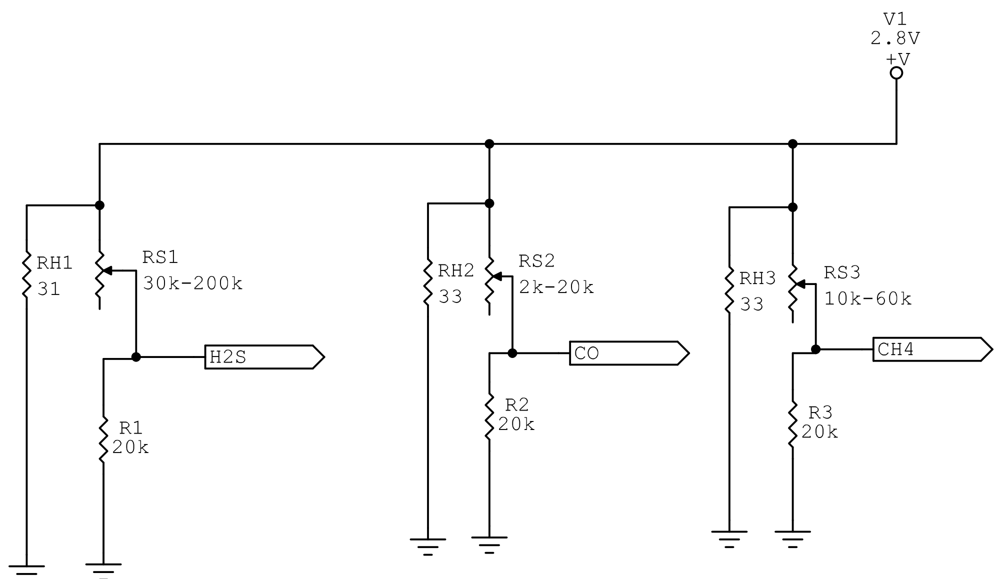

Figure 4.4: Equivalent Gas Sensor.

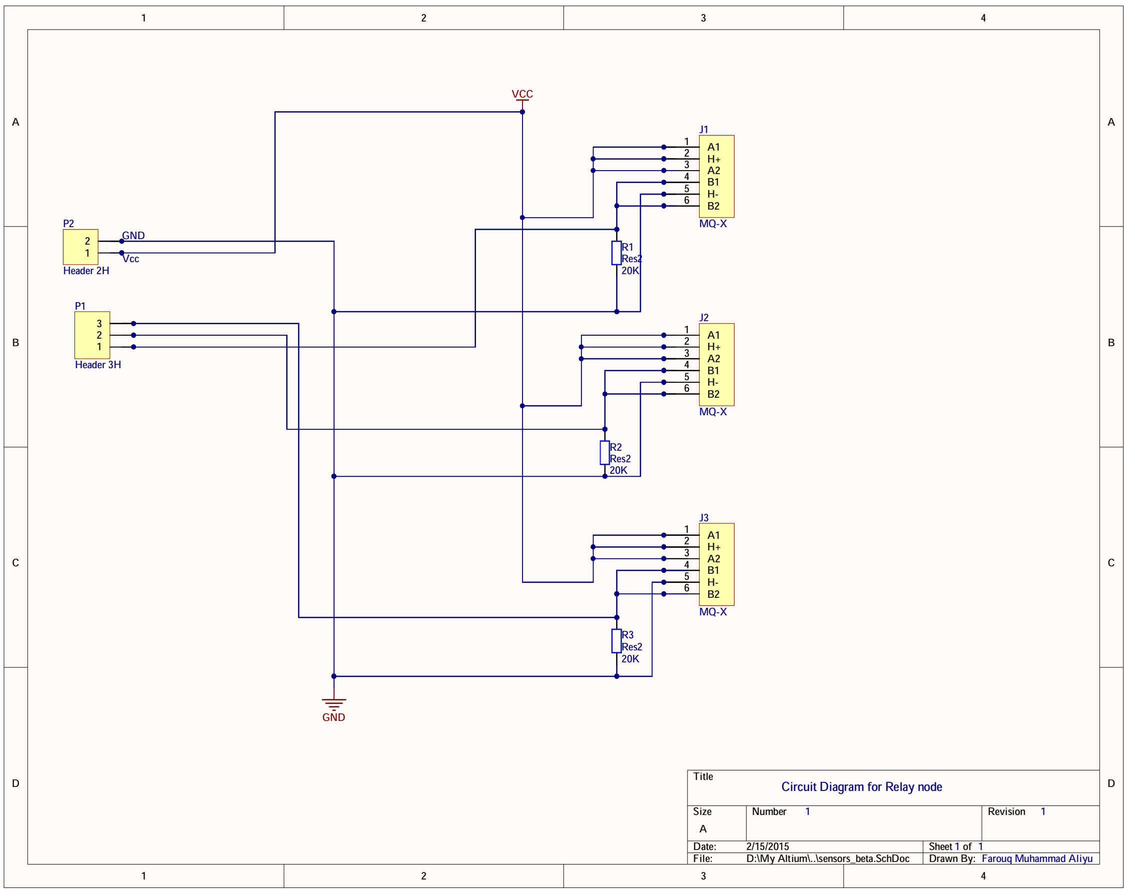

Figure 4.5: Circuit diagram for the Gas Sensor Node.

Gas Sensor

As mentioned earlier in chapter 2, semi-conductor gas sensor acts as a variable resistor whose resistance either falls or rises (depending on the semi-conduction's doping) during gas leakage. Figure 4.5 show the circuit diagram of the sensor used in the proposed sensor node and Figure 4.4 shows the equivalent circuit for the network of gas sensors. Each of the sensors is connected in a potential divider with $20k\Omega$ resistor and the voltage is measured with reference to the ground. From MQ-series sensor datasheet [103][104][105]: The resistance of the heater (see Section 2.4.4 for more information on semiconductor gas sensors) in the gas sensor is around 34Ω. The minimum resistance of the sensor is 30kΩ, 2kΩ and 10kΩ for H_2S, CO and CH_4 respectively. Therefore, the equivalent resistance of the network of resistor is $\approx 11.77\Omega$ as can be seen from Equation 4.1. Equation 4.2 shows the maximum amount of current flowing through the network of sensors at 2.8v is 260 mA. The voltage at across the sensor is 2.8v because some of the voltage is dropped across the logic MOSFET IRL520, which is used in switching the gas sensor network. From Although the semiconductor itself has resistance its effect is negligible.

$$
\begin{aligned}
R_{gas\_sensor} &= (31||(30\text{k} + 20\text{k})||(33||(2\text{k} + 20\text{k})||(33||(10\text{k} + 20\text{k}) \qquad (4.1)\\
&\approx 11.77\Omega\\
I_{gas\_sensor} &= \frac{2.8v}{(11.77\Omega)} \qquad (4.2)\\
&\approx 260mA
\end{aligned}
$$

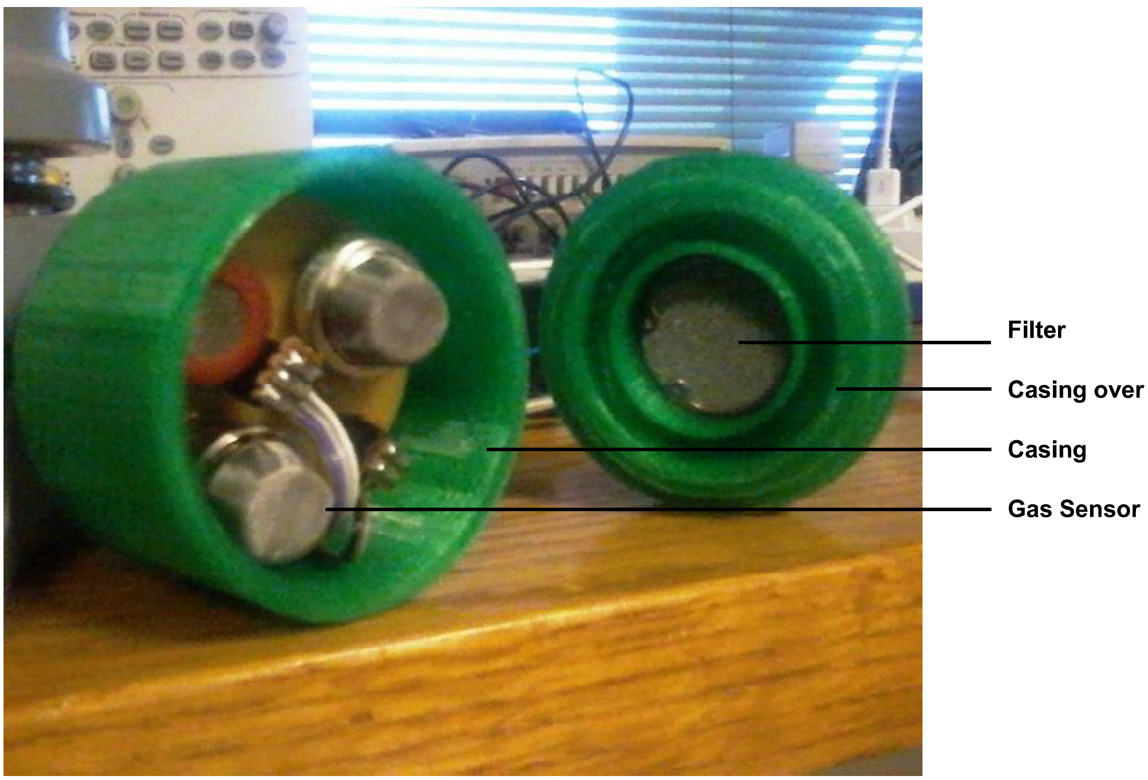

Figure 4.6: The Gas Sensor Casing.

The sensors were encased in a 3D printed container designed with Blender 3D software [106]. A hydrophobic filter in order to disable moisture from affecting the reading. The mechanical drawing can be found in Appendix C and the printed casing can be seen in Figure 4.6. The casing is meant to be made up of steal and the one in Figure 4.6 is just a proof of concept. The use of container allow the gas sensors to be protected from dust water and ambient temperature.

Wireless Transceiver

For wireless communication Zigbee protocol is chosen. Zigbee is chosen because: it is proven to be a durable network protocol for industrial applications [107], it allows for mesh networks, its transceiver is readily available and easy to use. Therefore, XBee Pro S2B is chosen as the wireless transceiver [108]. The zigbee transceiver has a different power rating than the other components on the board. Rather than +5v, the transceiver uses a +3.3v power supply. For this reason, the Xbee's Power Supply Unit (PSU) is designed separately. This transceiver consumes a maximum current of 205mA [108]. Adjustable voltage regulator is chosen because +3.3v fixed regulators are hard to come by in the market. Figure 4.7 shows the PSU designed and Equations 4.3, 4.5 and 4.6

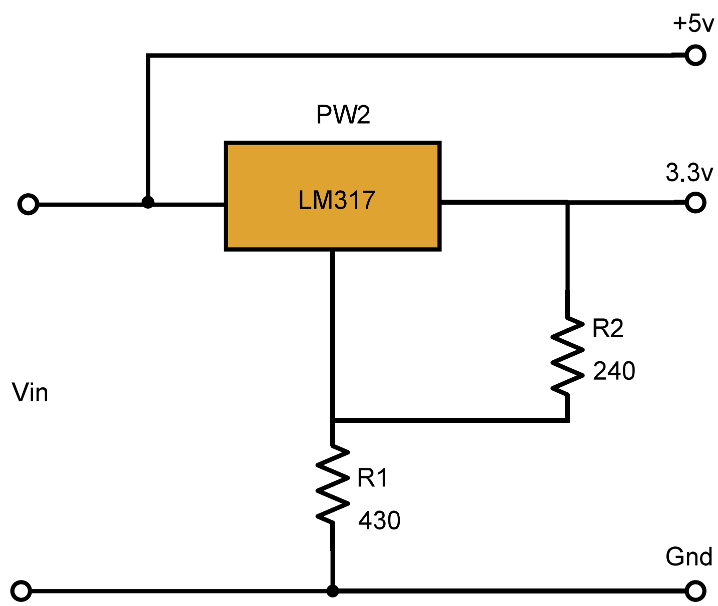

Figure 4.7: Power Supply Unit for the Xbee transceiver.

$$V_o = 1.25(1 + \frac{R_2}{R_1}) + I_{ADJ} \times R_2 \tag{4.3}$$

$Where;$

$$V_o = Targeted \quad output \quad voltage = 3.3v$$

$$I_{ADJ} = 100\mu A \tag{4.4}$$

$$R_1 = 240\Omega \quad (recommended \quad by \quad datasheet) \tag{4.5}$$

$$\begin{aligned} 3.3 &= 1.25(1 + \frac{R_2}{240}) + (100 \times 10^{-6}) \times R_2 \\ R_2 &= \frac{(3.3 - 1.25)}{((1.25 \times 240) - (100 \times 10^{-6}))} \\ &\approx 430\Omega \end{aligned} \tag{4.6}$$

The Zigbee transceiver communicates with the microcontroller through serial communication (UART). However, Atmega328 has only one UART port. As such, the Zigbee module is connect to Pin16 and Pin17 and software serial communication is used. Unfortunately the microcontroller does not have any pins with pin-change interrupt apart from the UART ports, hence our gas sensor can transmit but not receive.

Microcontroller Unit

For the mocrocontroller unit, Atmega328P is the only AVR with DIP package that can make a circuit board which will fit our explosion proof casing. The microcontroller can be powered by +5v with maximum current of 2mA at 16MHz clock speed. The microcontroller manages the activity of the whole system: It measures the battery an calculate the power that remains. It performs self check to make sure the basic components are working fine. It takes the gas reading process it and displays the output through the LCD — at the same time transmits it to the coordinator or broadcast it to the network.

In order to measure the energy remaining in the battery, a potential divider with a ratio 3:1 is connected across the power source just behind the receiver. The potential divider is necessary because the *Analogue to Digital Converter*'s (ADC) reference voltage is +5v. Therefore there is need to drop 12v battery source down to a level that can be read by the microcontroller. Equation 4.7 shows how the potential divider drops the voltage from +14v (full charged 12v batter) to +3.5v which can be read by the MCU. As such whenever the battery is full the Atmega reads 3.5v from the port labeled *Batt*. Resistors in the range of Mega-ohms where selected in order to ensure minimal power consumption by the potential divider.

$$Battery \quad Level = \frac{14 \times 1}{(1+3)} = 3.5v \tag{4.7}$$

The Atmega328p connects the LCD, GPS, Gas Sensor and the Zigbee transceiver. There is no need for pull-up or pull-down resistors, since all the components including the microcontroller work at TTL level except the Xbee PRO module. The module cannot receive data from the microcontroller, because the +5v is too high for it. This is because the microcontroller is transmitting at +5v

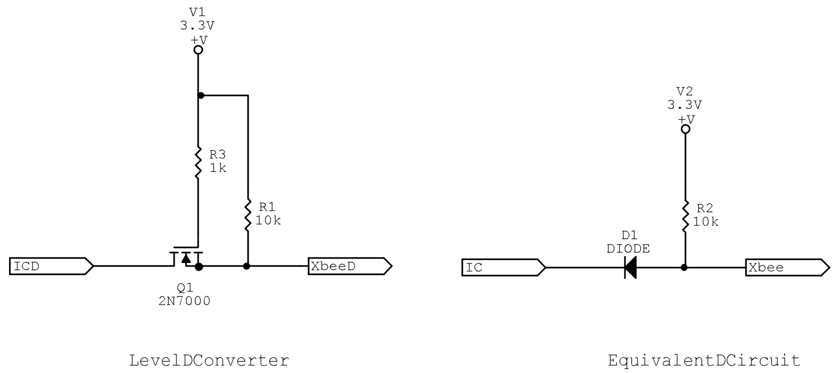

Figure 4.8: Circuit (left) and equivalent circuit (right) diagram for the level converter.

while the xbee module works on +3.3v only. Therefore, there is need for voltage level conversion from +5v to +3.3v. Figure 4.8 shows the level converter implemented (left) and the equivalent circuit (right). Resistors R1 and R2 are pull-up resistors and the diode is reverse bias when the microcontroller sends +5v. This blocks the +5v and replace it with +3.3v. However, when the mcrocontroller sends 0v the diode is forward bias, hence the 0v from the microconroller is seen at the Xbee's end.

The level converter is used to for all connections where signal moves from the microcontroller to the zigbee transceiver (i.e. Din and SLEEP ports in Figure 4.9).

Power Supply Unit Design

Each device has a rated working current and voltage. However, since most device of the devices have the same voltage but different current rating it is recommended to connect all components (i.e. LCD, Gas sensor, GPS and Microcontroller) in parallel. As such all the components will have the same (fixed) voltage but different current consumption. This forces the designer to design the system in relation to the current consumption of the components.

Let I_{total} be the maximum total amount of current consumed by the circuit. Since the voltage level of the components is known, finding the total current will allow us to choose the right voltage regulator for the system. The total current is the summation of the current consumed by the different components as shown in Equation 4.8.

I_{GPS} is the current consumed as a result of switching ON the GPS device. Therefore, $I_{GPS} = 44mA$ the resistance of the switching transistor IRL520 is neglected. I_{LCD} is the current consumed by the Liquid Crystal Display (LCD) is 3mA [101]. I_{IC} is the maximum current consumed by the Atmega microcontroller. $I_{IC} = 2mA$ according to the database [109].

$$\begin{aligned} I_{total} &= I_{IC} + I_{gas\_sensor} + I_{gps} + I_{LCD} \qquad (4.8) \\ &= 2 + 260 + 44 + 3 \\ &= 309mA \end{aligned}$$

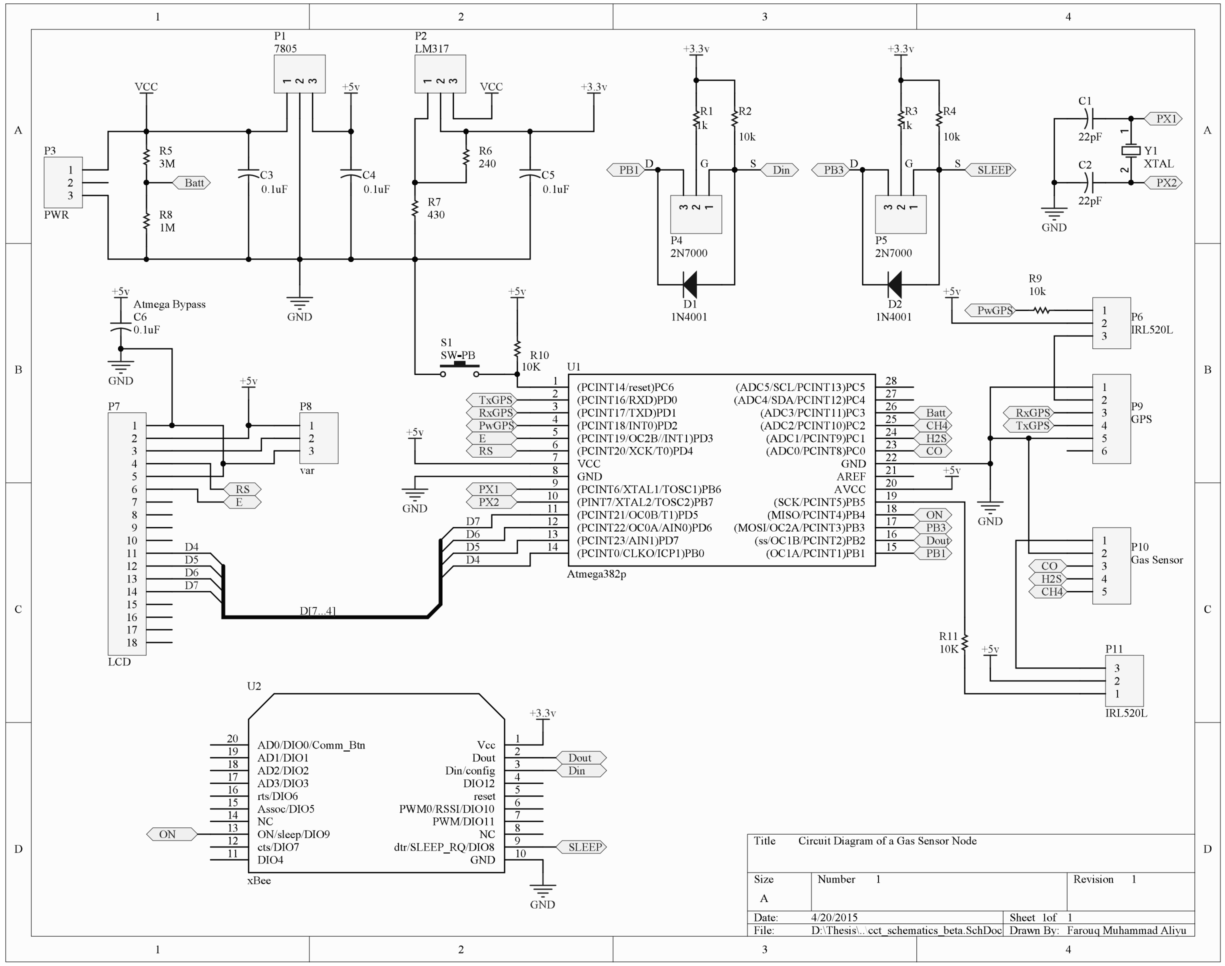

Figure 4.9: Circuit diagram for the Mainboard of the Sensor Node.

Figure 4.10: Sensor Node and its casing(Left) and the Sensor Node encased(Right).

$$P = (V_{in} - V_{out}) \times I \tag{4.9}$$
$$= (12 - 5) \times 309 \times 10^{-3}$$
$$= 2.163W$$
$$\theta_{JA(total)} = \frac{T_J - TA}{P} \tag{4.10}$$
$$But, T_A = 60^oC$$
$$T_J = 150^oC$$
$$\therefore \theta_{JA(total)} = \frac{150 - 60}{2.163}$$
$$= 41.6088^oC/W$$
$$\approx 42^oC/W$$

Since all components in Equation 4.8 require 5v to work properly, then the fixed regulator 7805, 1A is chosen. However, there is need to investigate the need for heat sink. The minimum Junction-to-Ambient thermal resistance of the regulator 7805 is $\theta_{JA} = 50^oC$ [110] and the calculated $\theta_{JA(total)} > \theta_{JA}$, then a heat sink is not needed [111].

For the sake of reliable, scalable and robust network zigbee protocol is chosen. Xbee Pro S2B transceiver was chosen for the network. However, the transceiver works on 3.3v power supply. Therefore, there is need for another regulator that will power the transceiver. Due to inaccessibility to fixed 3.3v regulator, a variable regulator (LM317) is chosen.

$$V_o = 1.25(1 + \frac{R_2}{R_1}) + I_{ADJ} \times R_2 \tag{4.11}$$

$Where;$

$$V_o = Targeted \quad output \quad voltage = 3.3v \tag{4.12}$$

$$I_{ADJ} = 100\mu A \tag{4.13}$$

$$R_1 = 240\Omega \quad (recommended \quad by \quad datasheet) \tag{4.14}$$

$$3.3 = 1.25(1 + \frac{R_2}{240}) + (100 \times 10^{-6}) \times R_2$$

$$R_2 = \frac{(3.3 - 1.25)}{((1.25 \times 240) - (100 \times 10^{-6}))}$$

$$\approx 430\Omega$$

In addition, energy harvesting through solar energy is included to the system. Figure 4.11 shows the circuit for the energy harvest. Positive terminal of the solar panel is connected to pin1 of the power socket while its negative is connected to pin3. Positive terminal of the battery is connected to pin5 while its negative is connected to pin7. Single pin is left in between each connection because of the form factor (size) of the power socket used. As shown in Figure 4.11, the current from the solar panel (I_S) feeds the board through the diode "D2". It also charges the battery through the diode "D1". The solar panel only charges the battery when its voltage is greater than the voltage of the battery as explained by Millman [112]. However, if the battery has greater voltage, the diode "D1" stops its current (I_B) from flowing into the solar panel — preventing the solar panel from being damaged. The current, I_B, flows through "D4" and "D2" to reach the main board. For all the diodes 1N4001 is chosen because it can handle currents of up to 1A and the maximum current of the gas sensor's main board is 309mA as calculated in Equation 4.8.

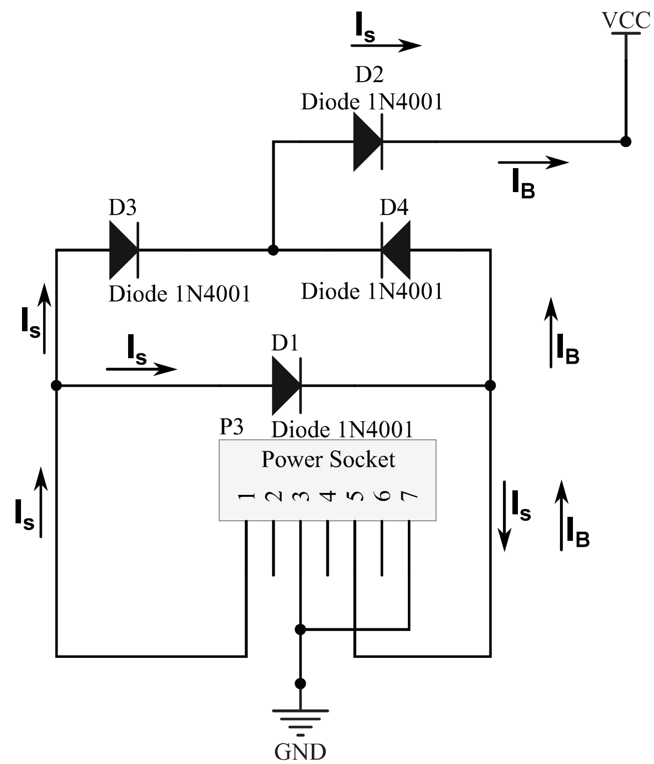

Figure 4.11: Energy harvesting circuit for the PSU.

Finally, the designed circuit in Figure 4.9 is simulated using Circuit Maker [113]. The circuit is then drawn in Altium Designer [114] where it is converted to PCB for printing. The PCB files can be made available upon request. A double layer PCB is printed using chemical process. The components were then place and the circuit is tested again. Some of the problems encountered during this test can be found in Appendix A. Figure 4.10 shows the final assembly of the system after all circuit tests are completed.

4.2.2 Relay Node

IEEE 802.15.4 MAC/PHY standards are written for short range applications. Therefore, one needs to somehow extend the network if one wants long range applications. Zigbee protocol has a solution to this problem. Relay node. A relay node as the name implies is a node that forwards packets to-and-for across the network. A Relay node is designed in this work and can be seen in Figure 4.17. This relay nodes do not require any special programming. The microcontroller is added in case solar panel is added to the it. In such configuration, the relay nodes can be deployed in pairs so that while one is relaying data the other is recharging its battery. Therefore, the relay node has a block diagram as shown in 4.12. Using the top-down approach in Section 4.2.1, the following design is accomplished:

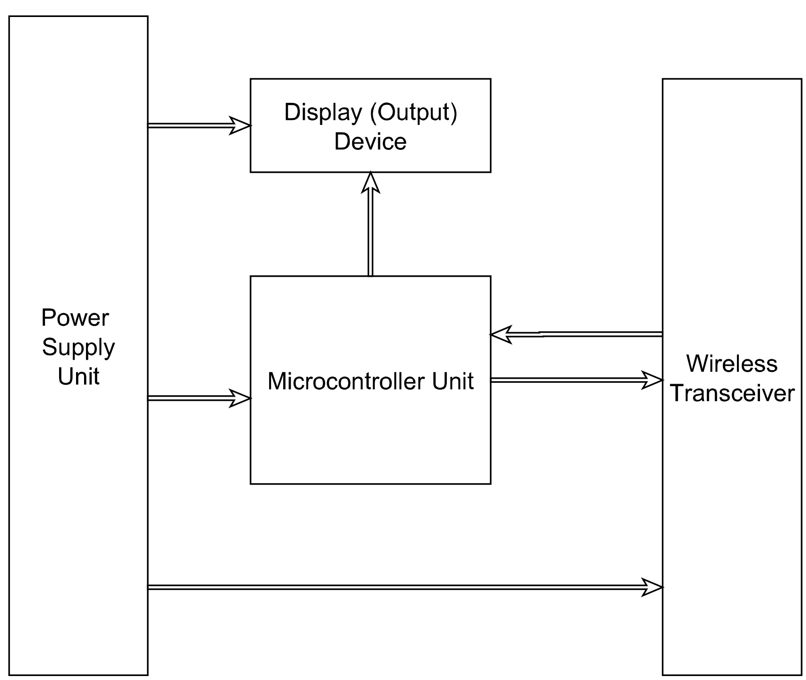

Figure 4.12: Block diagram for the Relay Sensor Node.

Display (Output) Device

An output device is needed in order to have observability [115] in the system. Unlike the Gas sensor there is little information to display here. The relay node needs only to display: battery level and error. Therefore an LED is just enough for a display unit. The LED uses +1.7v and consumes 15mA [116]. The relay node consists of three LEDs: Red, Yellow and Green. All the LEDs turn on when there is an error, while only Green-, Yellow- or Red LED turns on when the battery level is greater or equal to 100%, 75% or 25% respectively. Using Figure 4.13 and Equation 4.15, the circuit is designed as follows;

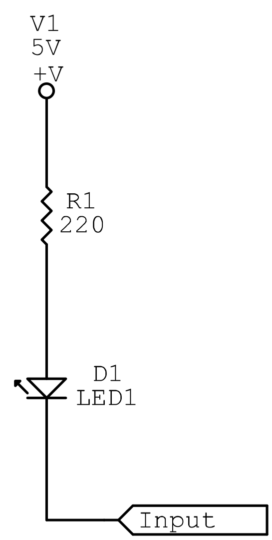

Figure 4.13: Circuit diagram for the LED display.

$$R_1 = \frac{V_{cc} - V_{led}}{I} \tag{4.15}$$

$$Since \quad components \quad are \quad in \quad series \quad I = I_{LED} = 15mA \tag{4.16}$$

$$\therefore R_1 = \frac{5 - 1.7}{15 \times 10^{-3}}$$

$$\approx 220\Omega$$

Wireless Transceiver

The wireless transceiver is designed in similar passion as the gas sensor's wireless module is designed in Sub-section 4.2.1.

Microcontroller

On the issue of microcontroller unit, Atmega328p is chosen. Since its only function is to make the relay node hibernate (sleep) during energy harvest, a smaller microcontroller like ATtiny10 should have been chosen. However, this microcontroller is not available. The relay nodes do not have any GPS device, therefore the Zigbee module is connected to the UART. This means that the relay node apart from its function of forwarding data, can receive command and reply to them.

Power Supply Unit (PSU)

The PSU consists of the same kind of energy harvesting circuit as that of the gas sensor shown in Figure 4.11. It also has two voltage regulators: +5v voltage regulator for the microcontroller and a +3.3v regulator for the wireless transceiver.

The wireless transceiver design is similar to that of the gas sensor in Section 4.2.1. The design for the +5v regulator is as follows:

$$\begin{aligned} I_{total} &= I_{IC} + 3 \times I_{LED} && (4.17)\\ &= 2 + 3 \times 15mA\\ &= 47mA \end{aligned}$$

$$V_{in} = 9v \quad \text{9v P3 battery is chosen since current consumed by the board is small.} \tag{4.18}$$

$$\begin{aligned} P &= (V_{in} - V_{out}) \times I && (4.19)\\ &= (9v - 5) \times 47 \times 10^{-3}\\ &= 188mW \end{aligned}$$

$$\begin{aligned} \theta_{JA(total)} &= \frac{T_J - TA}{P} && (4.20)\\ But, T_A &= 60^oC\\ T_J &= 150^oC\\ \therefore \theta_{JA(total)} &= \frac{150 - 60}{188 \times 10^{-3}}\\ &= 478.7234^oC/W\\ &\approx 478.7^oC/W \end{aligned}$$

Since $\theta_{JA(total)} > \theta_{JA}$ then a heat sink is not needed [111]. As shown in Equation 4.18, 9v P3 battery is chosen [117], since not much energy is consumed by the relay node. More reasons for this selection are: the relay node should be cheap and should have a small form factor because many are to be deployed.

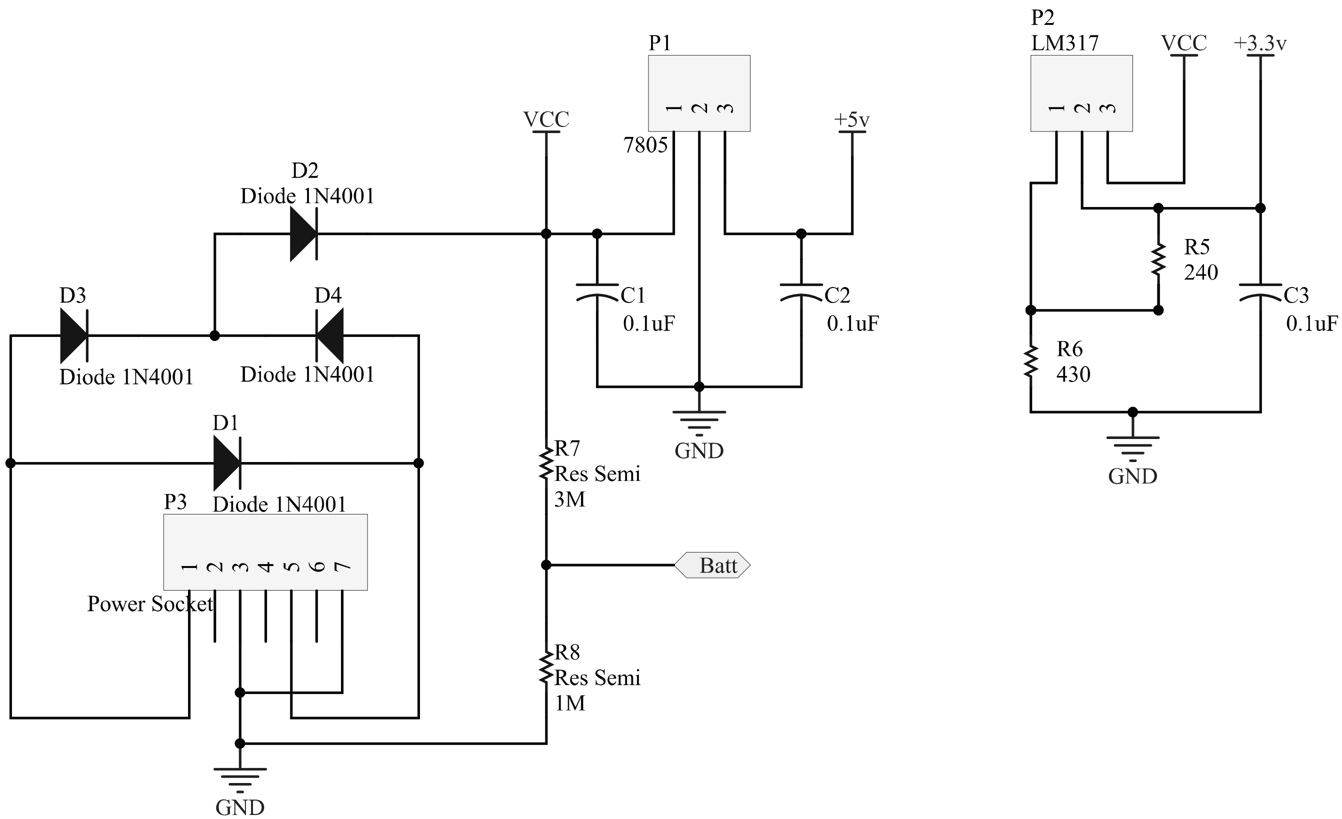

Figure 4.14: Circuit diagram for the PSU of the Relay Sensor Node.

4.2.3 Actuator Node

Apart from the relay node, an actuator is also designed. The actuator is powered through the mains power supply, therefore there is no need for either sleep or energy harvesting. The actuators are optional and may only be deployed when the network administrator requires a system that can automatically close valves during gas leakage to avoid further gas leakage.

The block diagram in Figure 4.15 shows the structure of the actuator. The actuator consists of a PSU that is powered by a +12v DC charger. The PSU is responsible for powering the components of the system shown in the block diagram. A wireless module is used to receive commands and gas levels from the network. This commands and gas levels are then processed by the MCU and the result is displayed in the output device. Furthermore, the MCU also controls the switching system based on the command received. The switching system is responsible for turning ON/OFF the valve. It is necessary because the MCU uses +5v DC while the valve uses 12v DC [118][119]. This voltage, obviously, is too much for the MCU as such a switching system isolating the two is needed. Following is the design of the Actuator.

Display (Output) Unit

The actuator node is mainly responsible for turning ON/OFF valve. Therefore, the possible information is can convey is mainly: Valve on, Valve off and Error. For this reason we used two lights. The green LED signifies valve on, the red

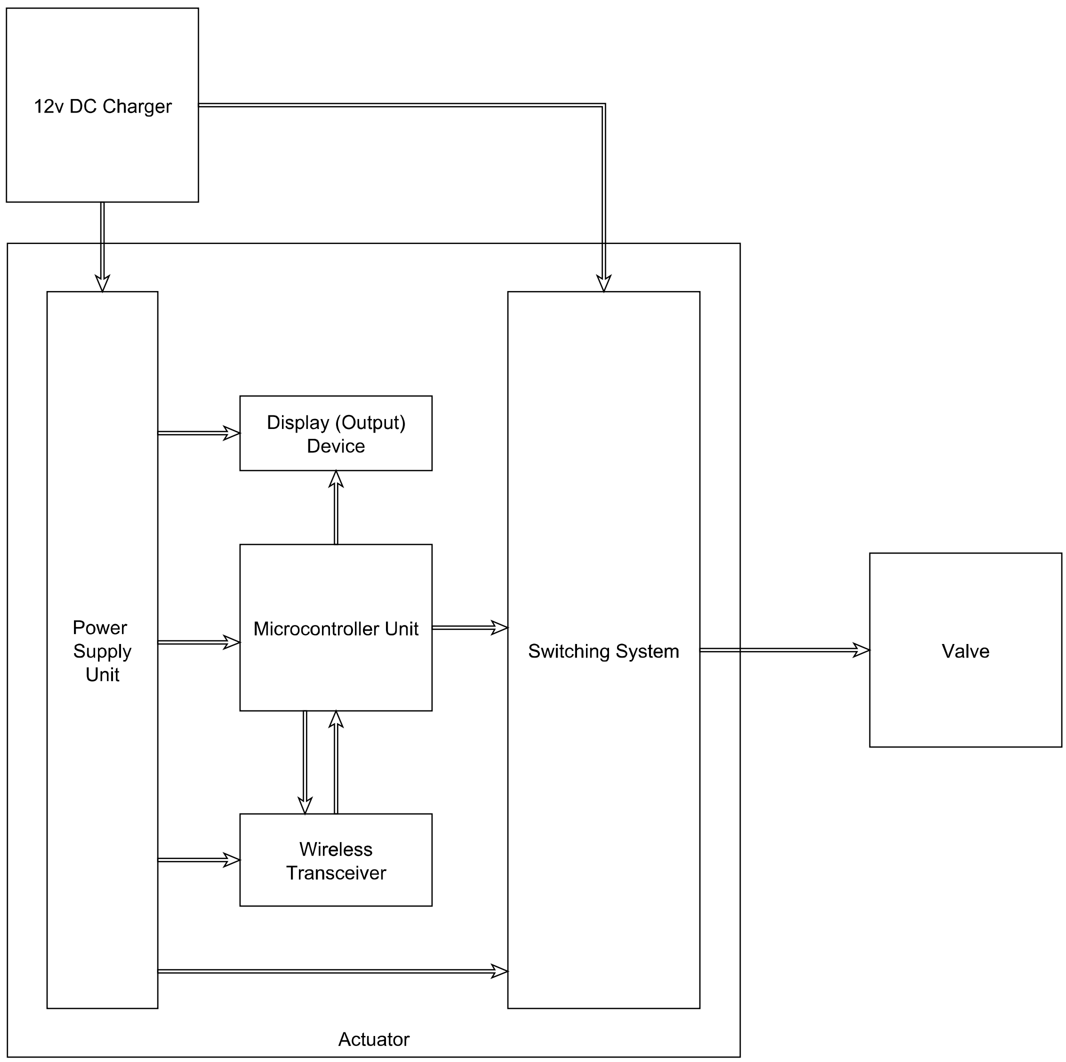

Figure 4.15: Block diagram the Actuator End Node.

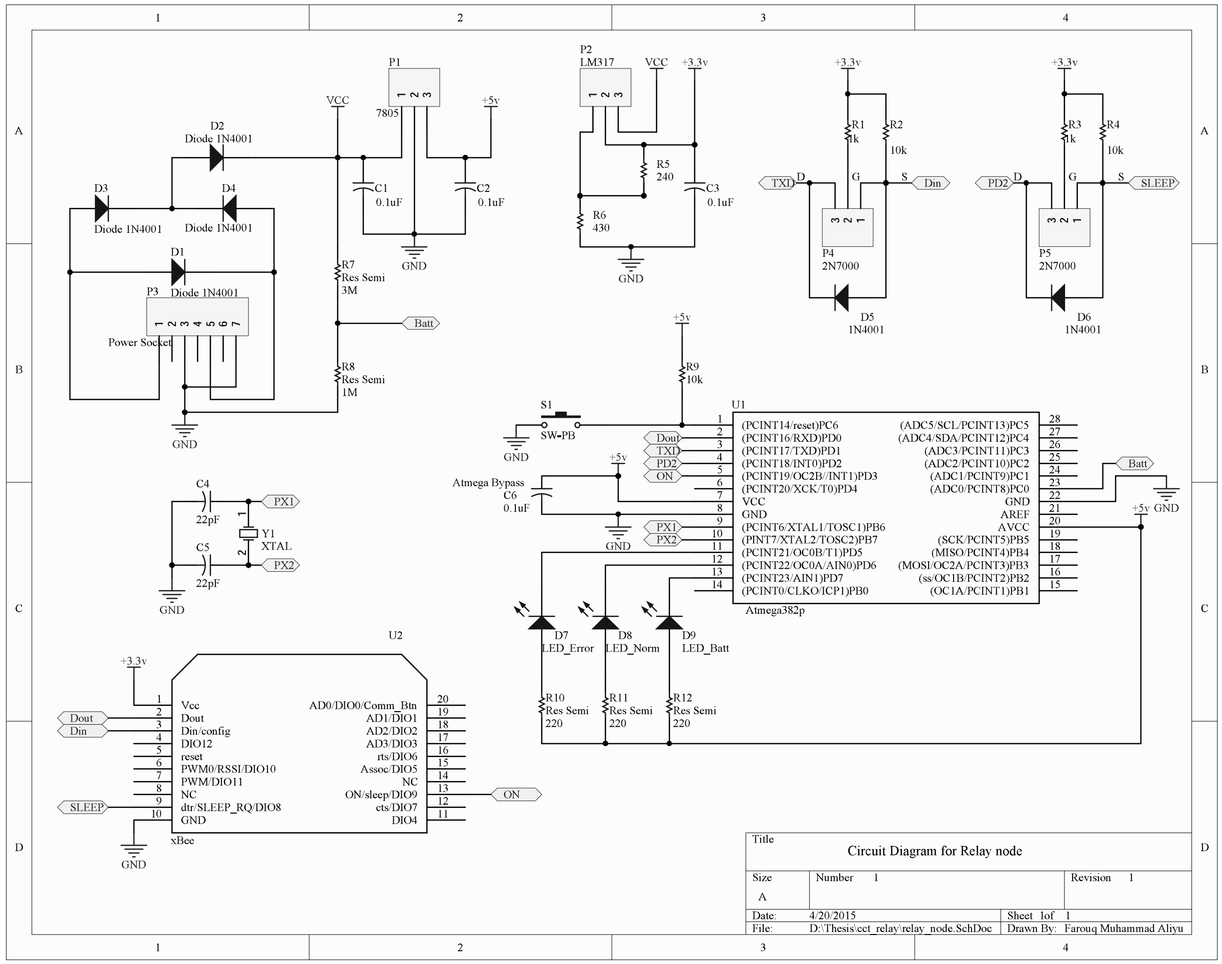

Figure 4.16: Circuit diagram for the Relay Sensor Node.

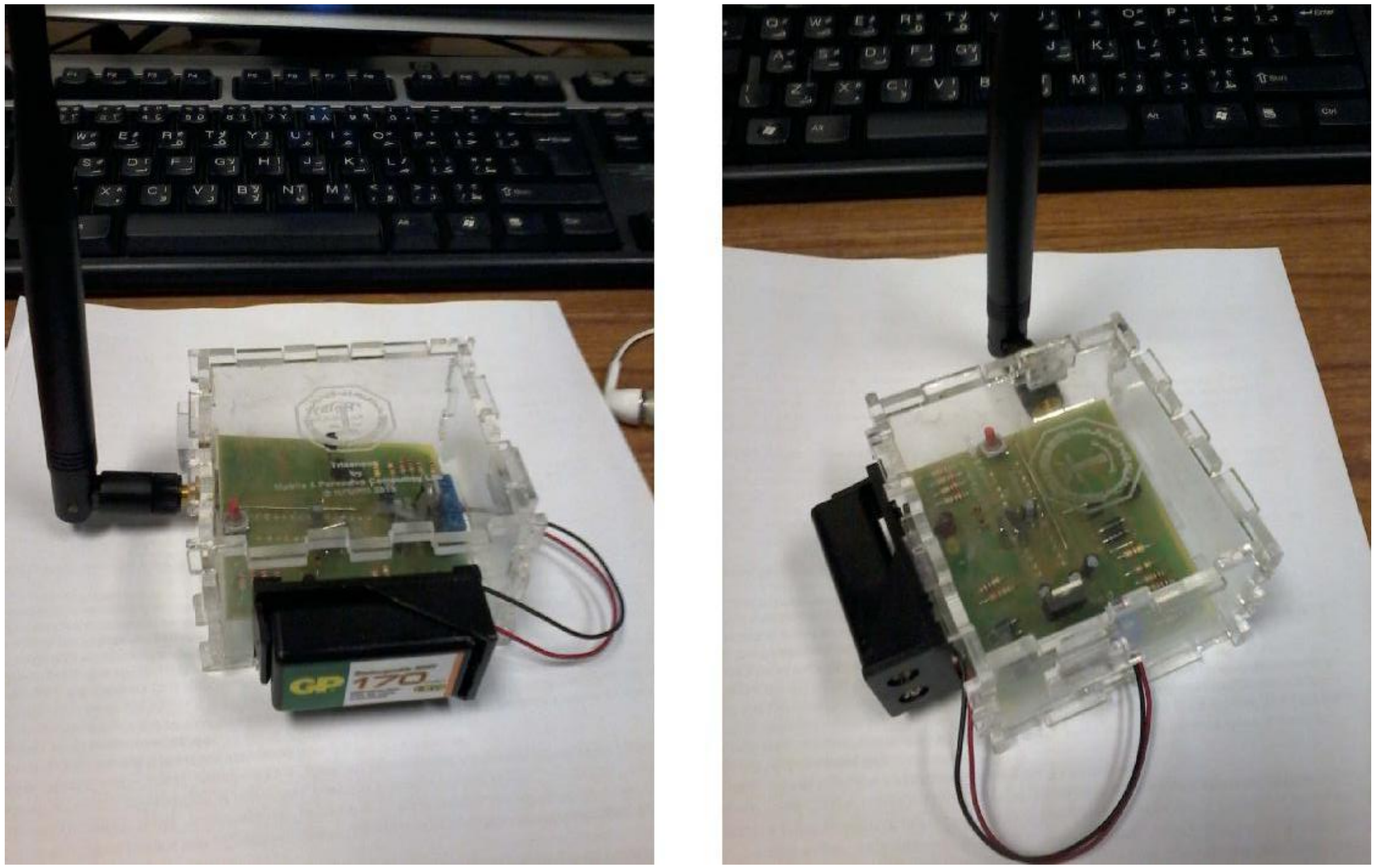

Figure 4.17: The complete Relay Sensor Node.

shows valve off while turning on both LEDs means error. Design for the LED is excatly the same as the design in Section 4.2.2.

Wireless Transceiver

The wireless transceiver is responsible for connecting the actuator to the network so that it can receive commands from the coordinator or gas readings from gas sensors. It has the same design as that of Section 4.2.1.

Switching System

Figure 4.18 shows the circuit diagram of the switching system. The system consists of a relay which is driving by a logic MOSFET (2N7000). In order to protect the MCU from gate dynamic current and the MOSFET from electrostatics a 10kΩ resistor is connected to the gate in series with the MCU. A freewheeling diode "D5" is connected across the relay in order to prevent back EMF from going back into the circuit. The relay is powered by +12v power sources and consumes a current of 33mA [120].

Microcontroller

A smaller microcontroller is should have been used, but Atmega328p is the one readily available. The microcontroller at 16MHz needs +5v and a current of 2mA. The Zigbee module is connected to the UART port of the microcontroller, therefore it can transmit and receive data. This gives the actuator node a lot of flexibility. For instance it can give the coordinator feedback of commands it receive

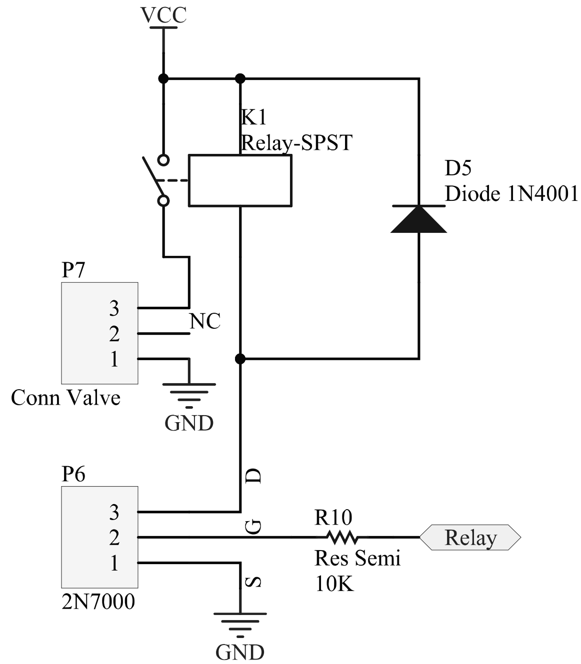

Figure 4.18: Circuit diagram for the Actuator End Node.

from the coordinator and it also means that the actuator can be programmed remotely.

Power Supply Unit (PSU)

The PSU uses power from the mains, therefore there is no need for energy harvesting circuit. However, two voltage regulators are needed: +5v voltage regulator for the microcontroller and a +3.3v regulator for the wireless transceiver. The wireless transceiver is designed as follows:

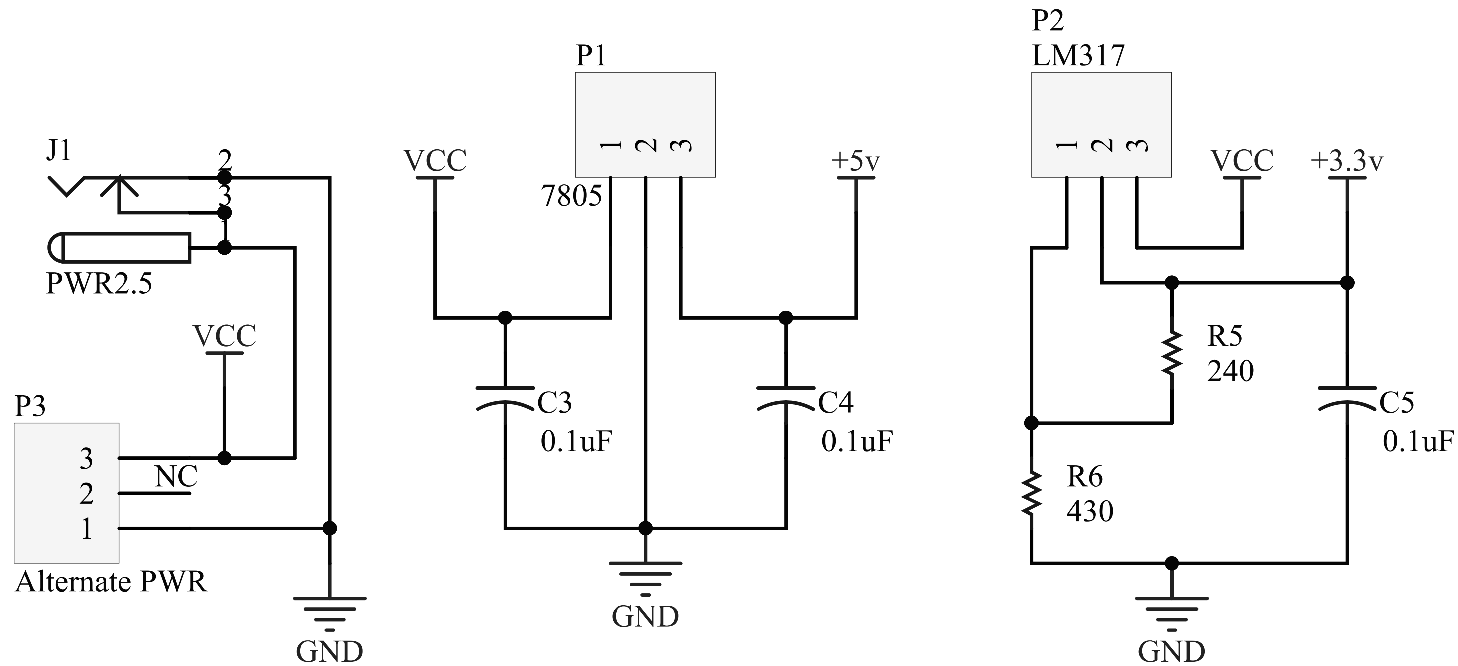

Figure 4.19: Circuit diagram for the PSU of the Actuator Sensor Node.

$$
\begin{aligned}
I_{total} &= I_{IC} + 2 \times I_{LED} + && (4.21)\\
&= 2 + 2 \times 15mA\\
&= 32mA\\
V_{in} &= 12v \quad \text{12v DC charger is needed because the relay need 12v to run.}\\
& && (4.22)\\
P &= (V_{in} - V_{out}) \times I && (4.23)\\
&= (12v - 5) \times 32 \times 10^{-3}\\
&= 224mW\\
\theta_{JA(total)} &= \frac{T_J - TA}{P} && (4.24)\\
But, T_A &= 60^oC\\
T_J &= 150^oC\\
\therefore \theta_{JA(total)} &= \frac{150 - 60}{224 \times 10^{-3}}\\
&= 401.7857^oC/W\\
&\approx 401.8^oC/W
\end{aligned}
$$

Since $\theta_{JA(total)} > \theta_{JA}$ then a heat sink is not needed [111]. As shown in Equation 4.22, +12v charger is necessary because that is the minimum voltage needed by actuator.

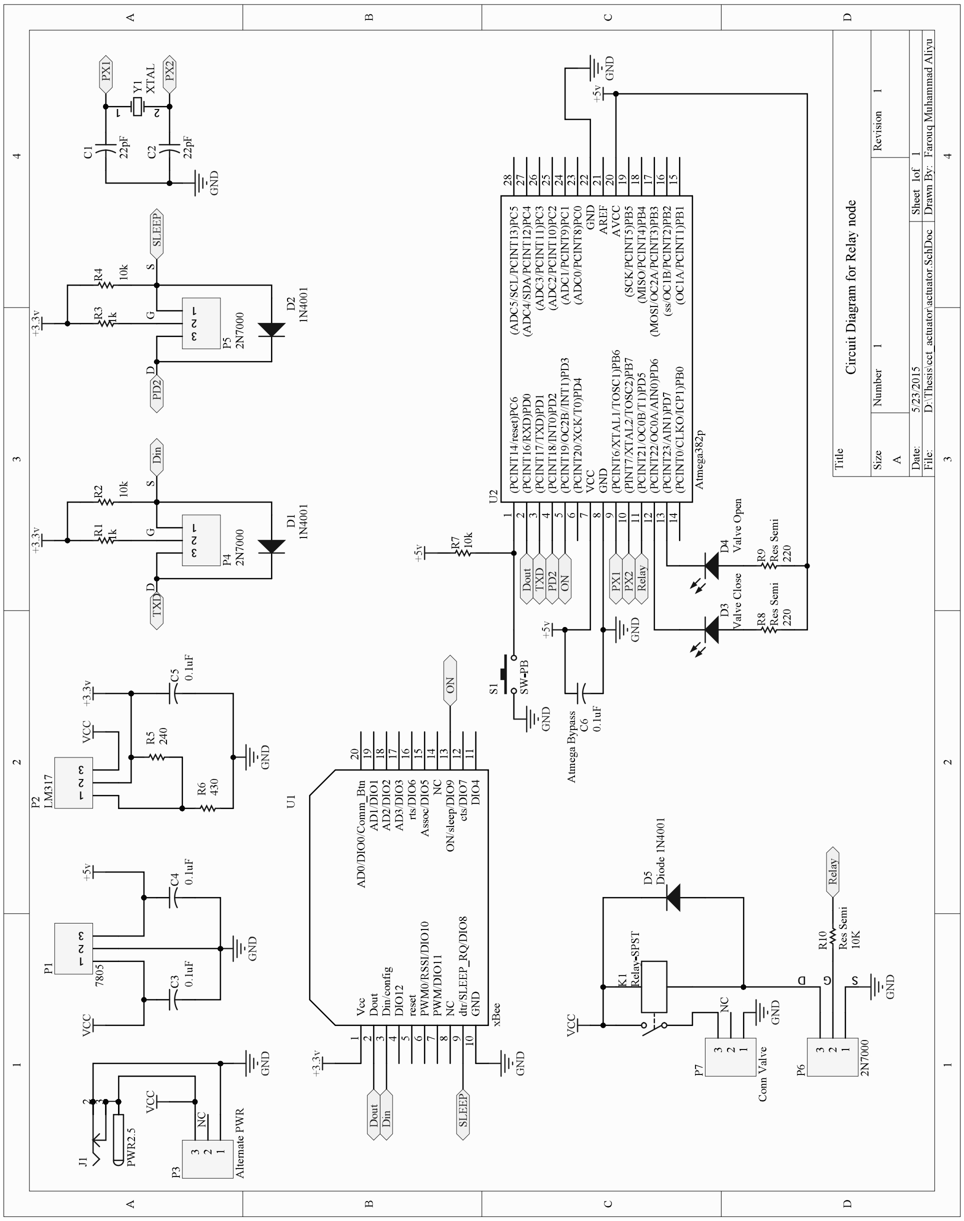

Figure 4.20: Circuit diagram for the Actuator End Node.

Figure 4.21: Final Actuator node.

4.3 Software Design and Analysis

The proposed system has two kinds of applications; a stand alone application that runs on the central computer and the embedded applications that installed in the nodes. Each class of node in the proposed system has its own application tailored to carry out their function with maximum performance and reduce energy consumption. However, the relay node and the coordinator node require no firmware. These two do not need any extra coding to work properly. In this section, a standalone application and an embedded application for the central computer and the sensor node are developed respectively. Although the actuators hardware is extensively tested an found to be working as expected, its firmware has not been completed up to the time of compiling this document.

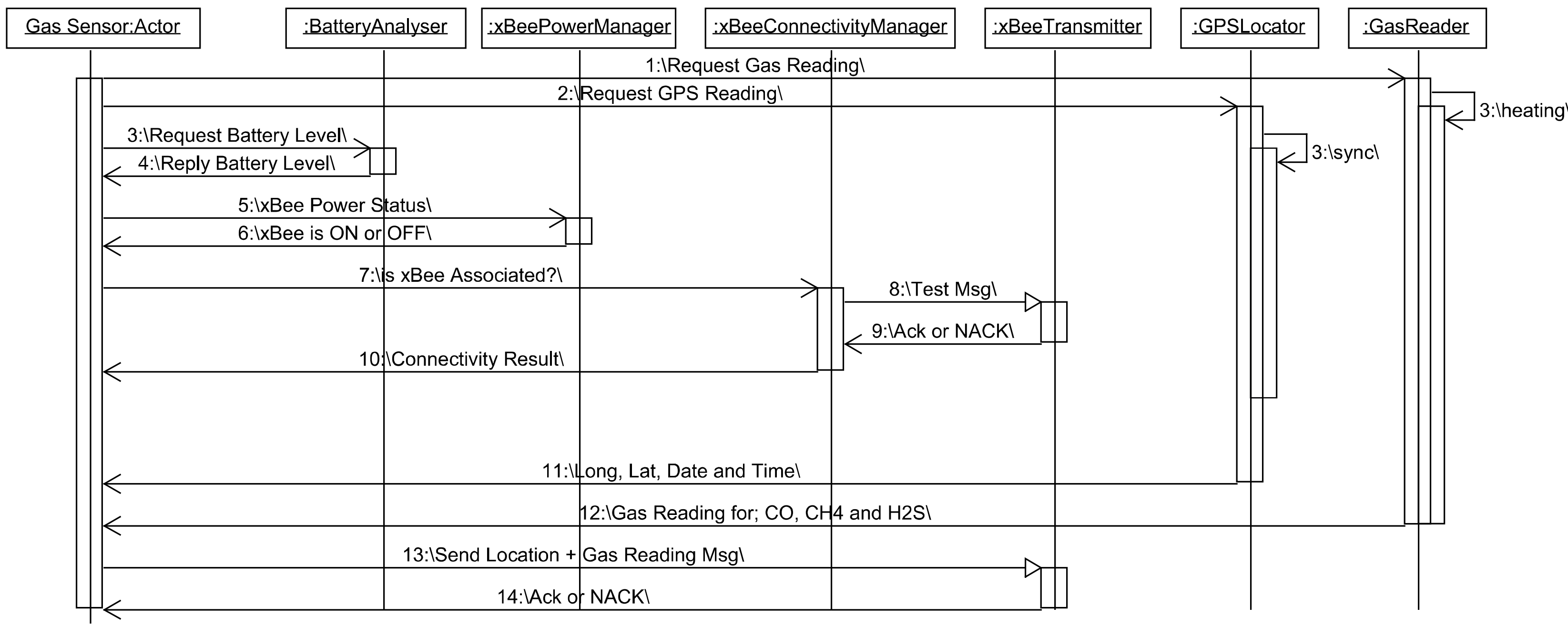

Figure 4.22: Sequence diagram for the Gas Sensor Node.

Algorithm 1 Battery Level Calculator

$Vlow \leftarrow 627$
$Vhigh \leftarrow 706$
$Vout \leftarrow 0$
$Vlow \leftarrow 627$
$maxCount \leftarrow 30$
$For(i = 0; i < maxCount; i++)\{$
$Vout \leftarrow Vout + analoguebattery$
$\}$
$Vout \leftarrow \frac{Vout}{maxCount}$
$percent \leftarrow (1 - (\frac{float(Vhigh-volt)}{float(Vhigh-Vlow)})) * 100$
$return(percent)$

Embedded Application for Sensor Node

Figure 4.22 shows the sequence diagram for the embedded application installed in the sensor nodes. The sensor node turns on the heater for the gas sensor and the GPS is also power. The node then allows the gas sensor to heat up. The node also allows the GPS module to synchronize with GPS satellites while it carry out other activities. These activities include reading the battery level as shown by Algorithm 1.The ON/OFF signal of the Xbee module is checked in order to ensure that the Xbee module is powered. The Xbee's connectivity is also checked by broadcasting test packet and listening for reply from the coordinator. The node the goes back to the GPS device for GPS location. Finally the gas reading is fetched and broadcasted.

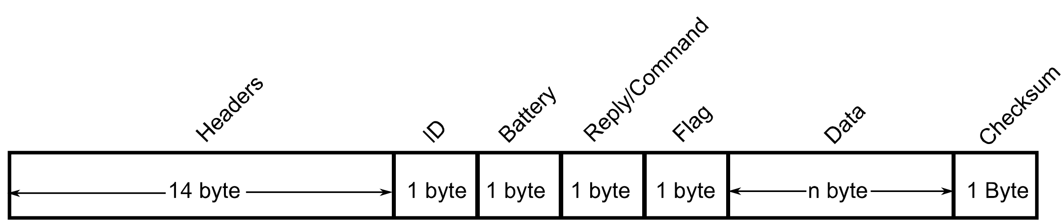

Figure 4.23: Format for transmitted packets.

Figure 4.23 show the format of the API packet [108][121] that is transmitted by the sensor node. The first 14 byte are headers files that include payload size, 64bit MAC address and 16bit network address of the sender. The checksum is at the end of the packet. *ID* represents the node type, it is a positive integer, where 0, 1, 2 and 3 represents Coordinator, Sensor, Actuator and Router nodes respectively. *Battery* represents the percentage battery level of the sensor that is transmitting the data, hence it is an integer value ranging from 0-100%. The *Reply/Command* communicates instructions or reply to those instruction. Some of the few instruction available now are *No command*, *reset*, *Close* and *Open valve* represent by positive integers 0, 1, 2 and 3 respectively. *Flag* represents error encountered by the Xbee module. A certain bit is set high whenever a specific error occurs. Table 4.1 shows the different types of errors and the bit that represents them.

Table 4.1: Flag and their binary representation

Flag	Representing Bit's Position
No Commands	0
-	1
Battery	2
-	3
-	4
GPS Locator	5
Gas Reader	6
Error	7

Finally, when the sequence of evens shown in Figure 4.22 are exhausted and the node enters an infinite loop. The loop is shown in Figure 4.24, where the sensor sleeps for 2 minutes or 1 minute depending on where there is gas leakage or not respectively. The system also sound alarm during gas leakage and never turns it off unless the gas leakage seizes.

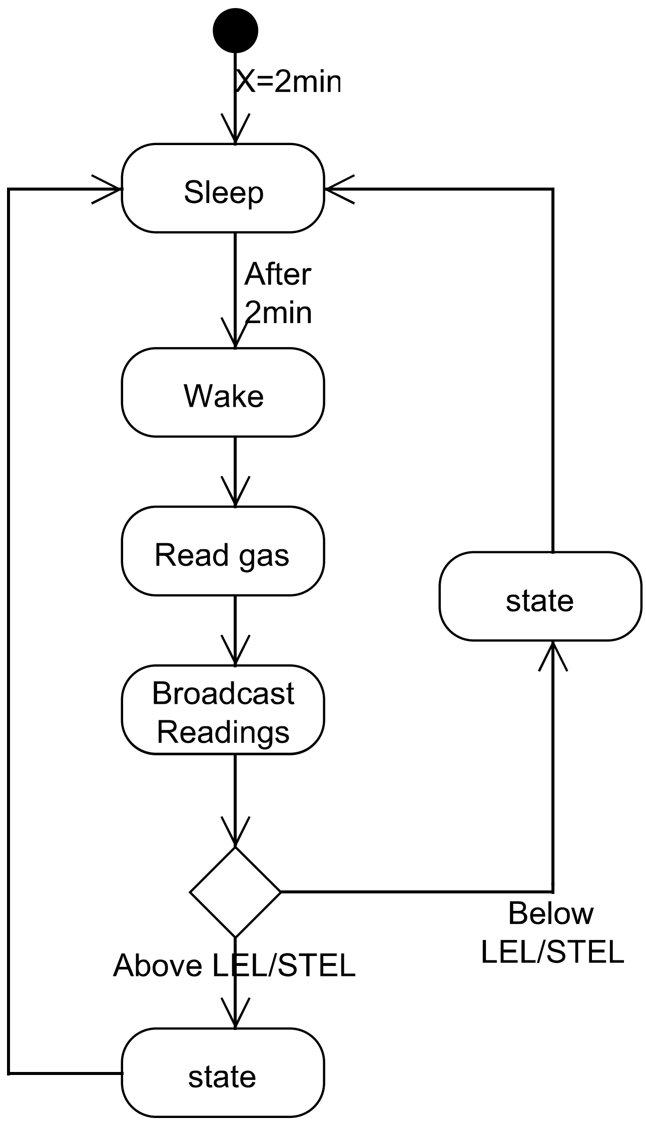

Figure 4.24: State diagram for the infinite loop of the Sensor Node.

Standalone Application for Workstation

Our proposed network is connected to a workstation, where the network administrator can over see all gas readings as well as the network at large. This connection is made possible by the coordinator. The coordinator serves as a sink to the sensor network and a gateway between the network and the said workstation. It is worth noting that the coordinator does not require any microcontroller, special circuit or extra embedded programming. The coordinator is already equipped firmware that can collect data from the network and send it to the workstation via serial port.

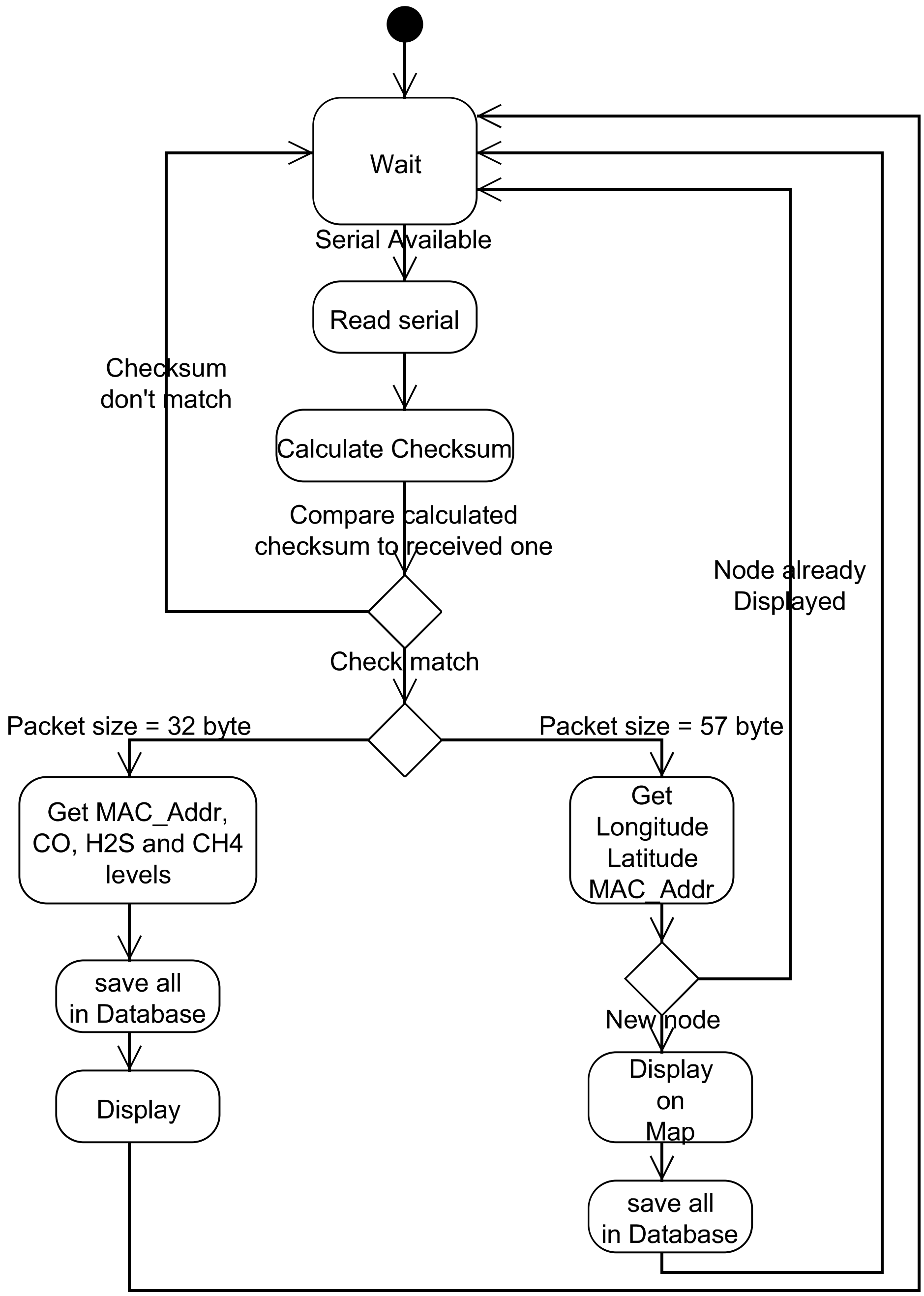

Figure 4.25: State diagram for the standalone application for the workstation connected to the coordinator.

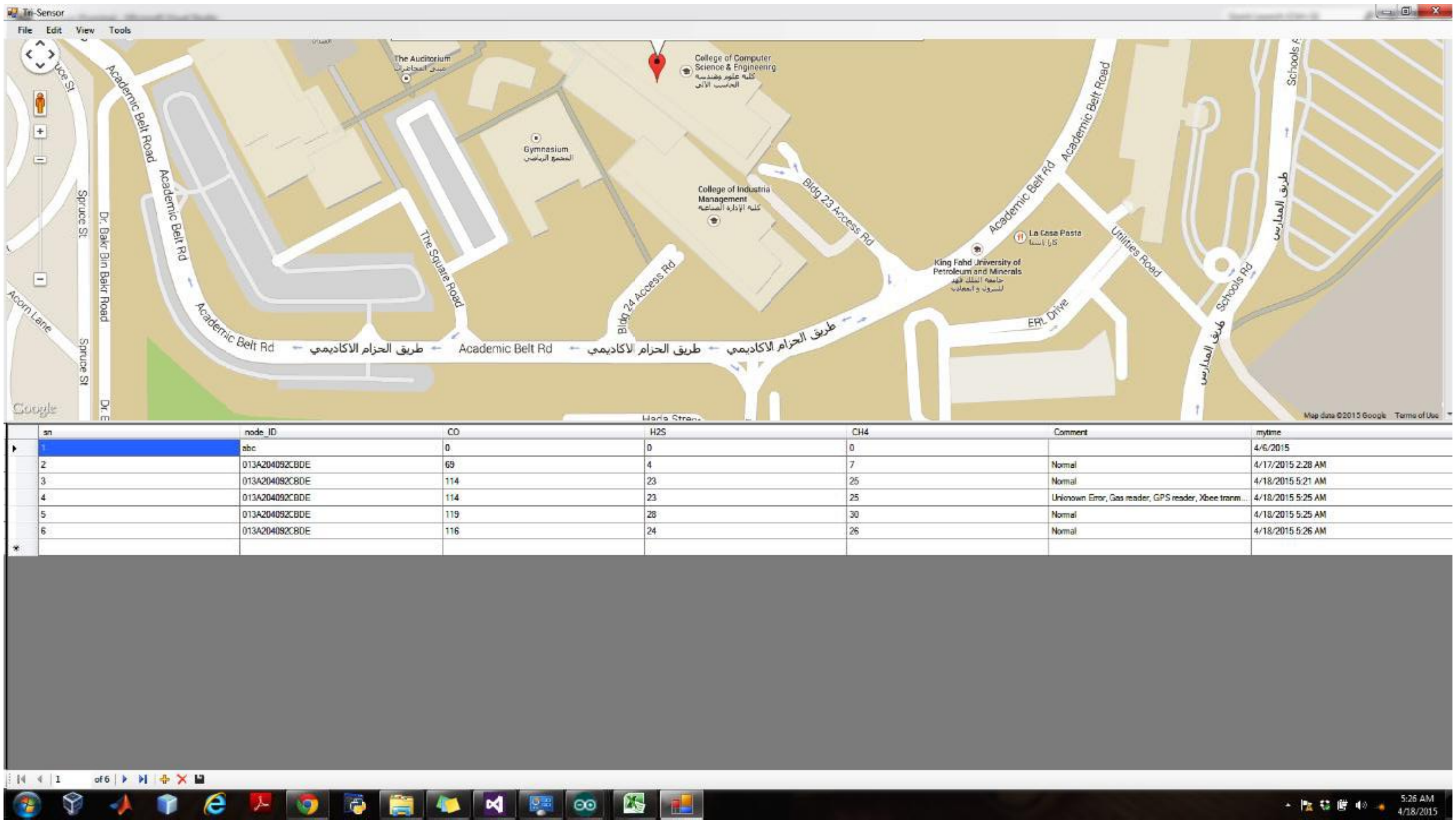

Figure 4.26: Screen shot of the standalone application for the workstation connected to the coordinator.

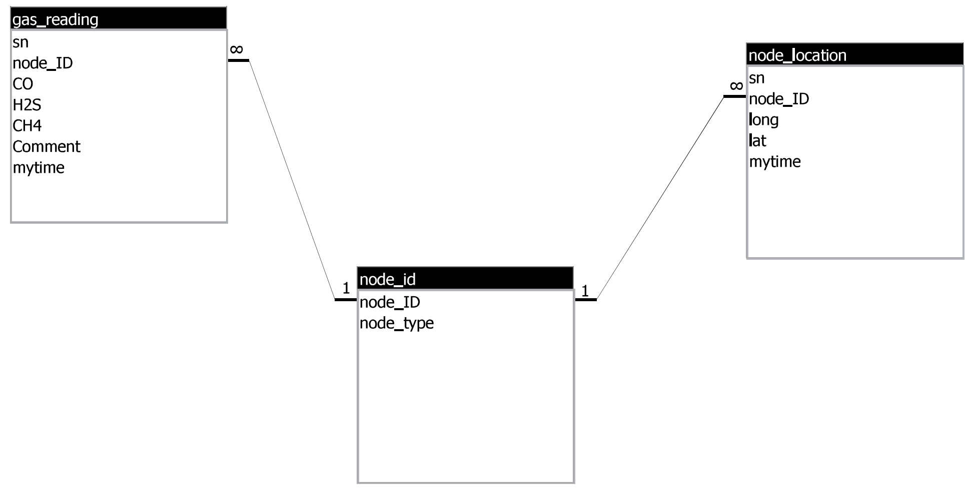

Figure 4.27: Relationship diagram of the database where sensor node's information is saved.

Moreover, the workstation is programmed to receive data from the sensor network and process it as shown in Figure 4.25. The application shown in Figure 4.26, listens to the COM port selected by the user. As soon as serial data is received, checksum is calculated using the formula in Equation 4.25. The calculated checksum is compared with the received checksum (i.e. the value in the last field of the frame). The system returns to its waiting state when there is no match, else the system moves on to check the packet size. The packet size determines the kind of packet sent without engaging in any complex computation, when the packet is 57 bytes long it is assumed to be the location of the node. As such the MAC Address, longitudes and latitudes are extracted and the new node is display on the map, if it is not previously displayed. However, if the packet size is equal to 32 bytes, then it is assumed to be the gas reading. The application then extracts the MAC Address and the level of the three gases in the atmosphere. The gas readings and the address are then saved in a database and also displayed on the screen before the application goes back to its waiting state. All information concerning the node are saved in a database, whose schema is shown in Figure 4.27.

$$Checksum = 0\mathrm{x}FF - (((\sum_{n-1}^{k=3} field_k) \quad mod \quad 0\mathrm{x}FF) \cdot 0\mathrm{x}FF) \tag{4.25}$$

4.4 Summary

In this chapter detailed design and analysis of the proposed system is provided. The proposed system has a sensor node with three gas sensors and a Zigbee transceiver. The sensor node checks the presence and level of carbon monoxide, Hydrogen Sulfide and Methane. The readings are broadcasted to the network. As soon as the readings reach the coordinator, they are saved in a data base and displayed in on the screen for tracking purpose.

CHAPTER 5

EXPERIMENTS AND RESULT

5.1 Introduction

In this section the performance of the proposed system is measured. This section is focused on energy consumption of the system since network performance of the Zigbee module is already investigated by many [122][123]. The energy consumption of the sensor node is investigated. Different components of the sensors were tested for energy consumption and it was found that the gas sensors were the most consumers of energy.

Accordingly, a second experiment was carried out to investigate the best possible way to use the gas sensor without incurring the already huge energy consumption. The experiment consists of investigating whether direct powering or switch powering will provide optimum power consumption to the system. We also investigate what duty cycle is best for powering the sensor if one chooses to use switch powering technique. Switch powering technique is a technique where by a gas sensor is powered by continuous pulse [95][90].

Finally,a system test is carried out. This experiment helps ascertain whether the system has reached the requirements outlined in Chapter 1. Due to the danger of experimenting with the gases involved in the proposed system, the behavior of the gas sensors was modeled from the sensors' datasheets and the model is the programmed on an Arduino mega 2560 microcontroller. The microcontroller is then connected to the sensor node. It is worth noting that the sensors firmware is not tempered with in anyway. The behavior of the system observed is then reported herein.

5.2 Sensor Node Experiment

First experiment is aimed at investigating the general energy consumption of the system during long duty cycles and short ones. The experiment also verifies the whether the sensor node can go to sleep and whether it can change the length of its sleep period upon gas leakage. Figure 5.1 shows the change in energy consumption overtime which is indicative of sleep and wakeup states of the node. This conclusion is arrived at given the fact that the sensor node sleeps for 2min in long sleep- and sleeps for 1min in short sleep sessions as pre-programmed. It should also be noted that the sensor wakes up for atleast 1min in both cases due to the minimum time it takes to heat the sensor.

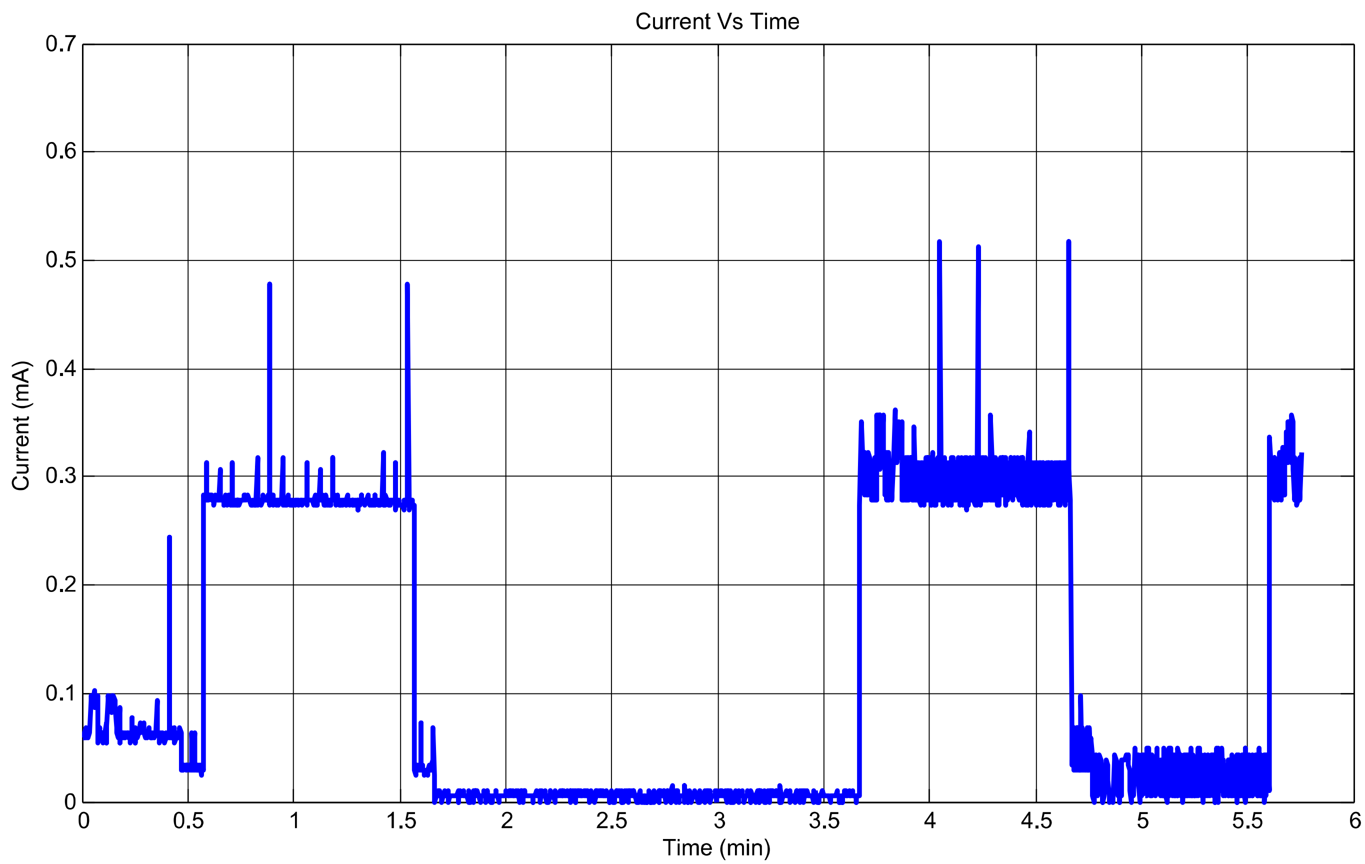

Figure 5.1: Current consumption per duty cycle.

During the wakeup state the node consumes around 300mA (1.5W). The spikes only seen during wakeup period are due to the Xbee transceiver, as such they are absent during sleep period because the transceiver is hibernated.

To further investigate the extent of energy consumption of the key components of the sensor (i.e. Liquid Crystal Display(LCD), Sensor, Transceiver, Microcontroller and GPS module), an experiment where each component is turned on to 10sec while others are turned off is carried out. A grace period of 5secs is given between the turning off of one component and the turning on of another. This allows for easy reading because overlaps are avoided. The sensor nodes are turned on in the following sequence;

1. LCD,
2. Gas sensor,
3. GPS module,
4. Xbee transceiver and
5. Microcontroller.

From Figure 5.3 it can be seen that the LCD consumes negligible amount of current, this is because the crystal of the LCD have very high resistance. As such most of the energy consumption of the LCD is due to its micorcontroller (i.e. HD44780U). The Gas sensor has the largest energy consumption of up to 260mA, due to the platinum coil heater as discussed in Section 2.4.4. The Xbee module comes second with peak current consumption of 60mA. GPS consume a maximum of 45mA while the microcontroller when it is not sleeping consumes 20mA and an average of 5mA in sleep (Hibernate) mode.

5.3 Gas Sensor Experiment

The fact that the gas sensor consumes 66.8% of the total current consume per sleep cycle is a concern. Hence experiments were carried out to measure the energy consumed by the sensor and the switching technique of powering it were also investigated.

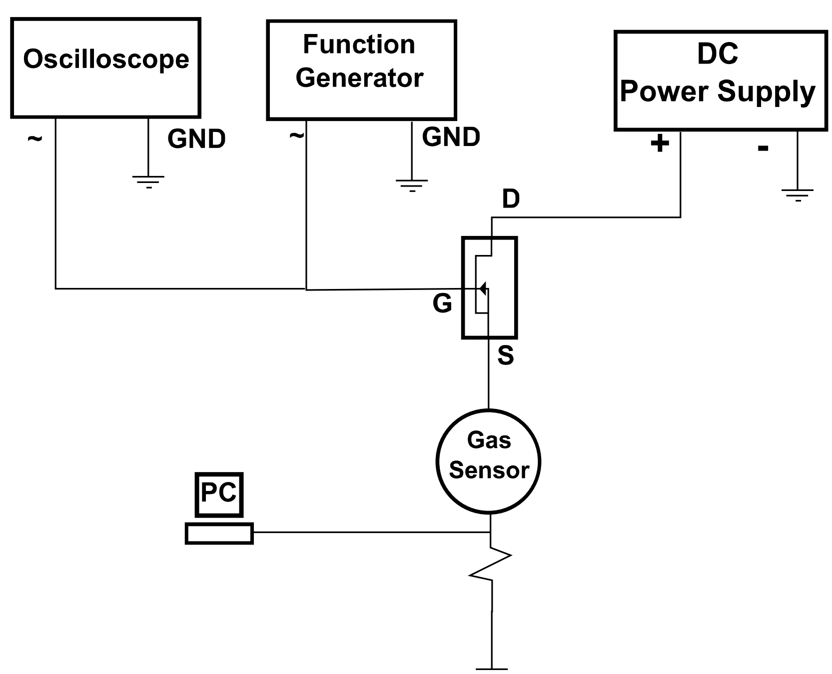

Figure 5.2: Experimental setup for investigating Gas sensor energy consumption.

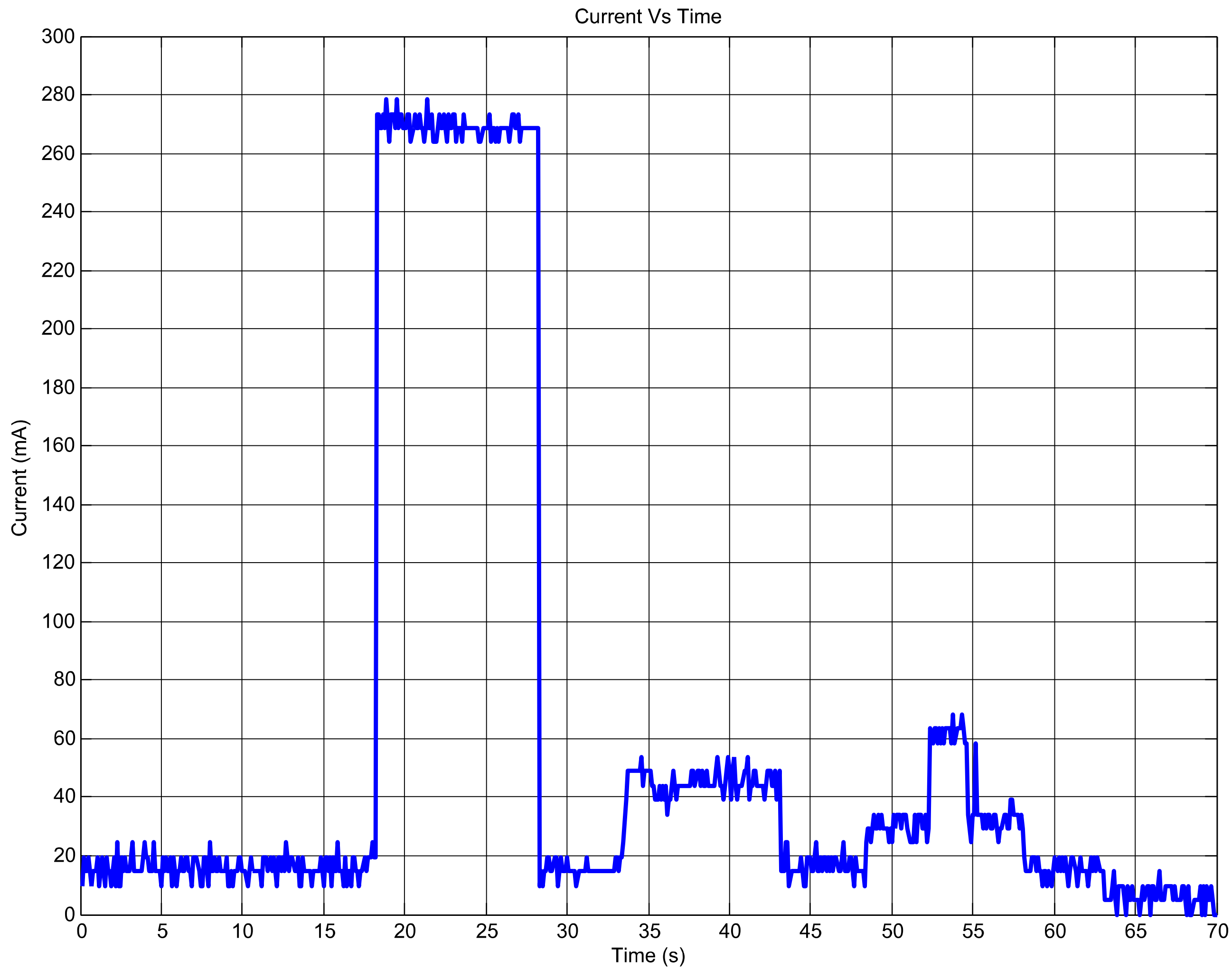

Figure 5.3: Power consumption of main components of the sensor.

As shown in Figure 5.2, IRL520 logic MOSFET is connected in series with the gas sensor, so that it can power the sensor when switched on by the function generator. An oscilloscope is also connected to the setup in order to ensure observability — so that the user can keep track of the experiment and ensure that nothing goes wrong. Voltage dropped across the 1Ω resistor is recorded because it equals the instantaneous current consumed by the system. Figures 5.5, 5.4, 5.6, 5.9, 5.7 and 5.8 are the results obtained from the experiment.

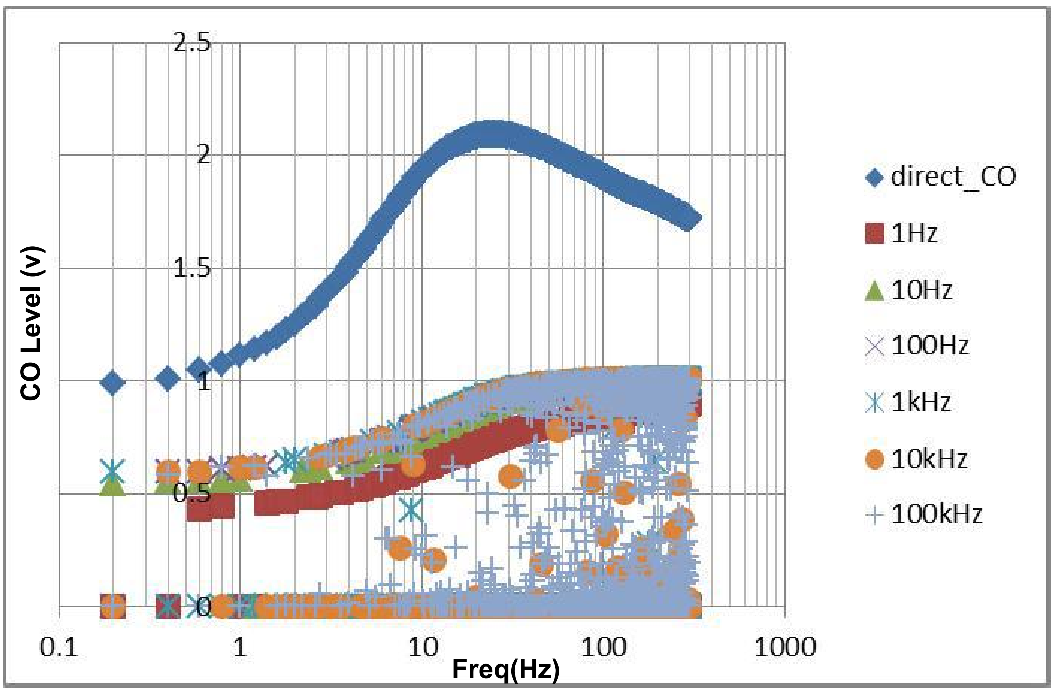

Figure 5.4: Graph of Carbon monoxide against time over different frequencies.

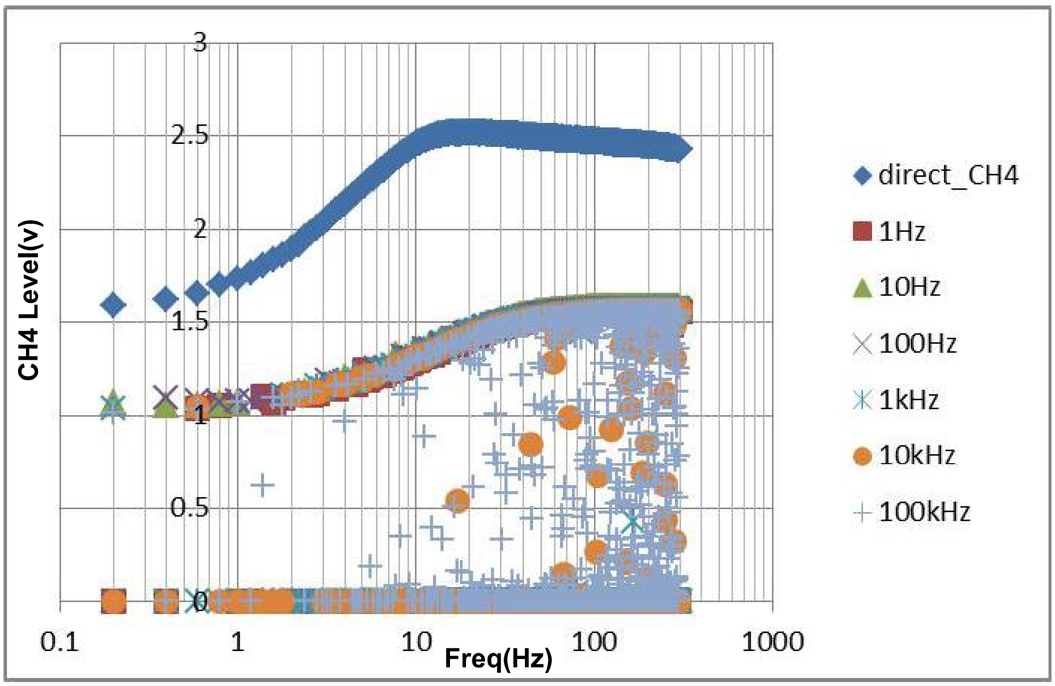

Figure 5.5: Graph of Mathane against time over different frequencies.

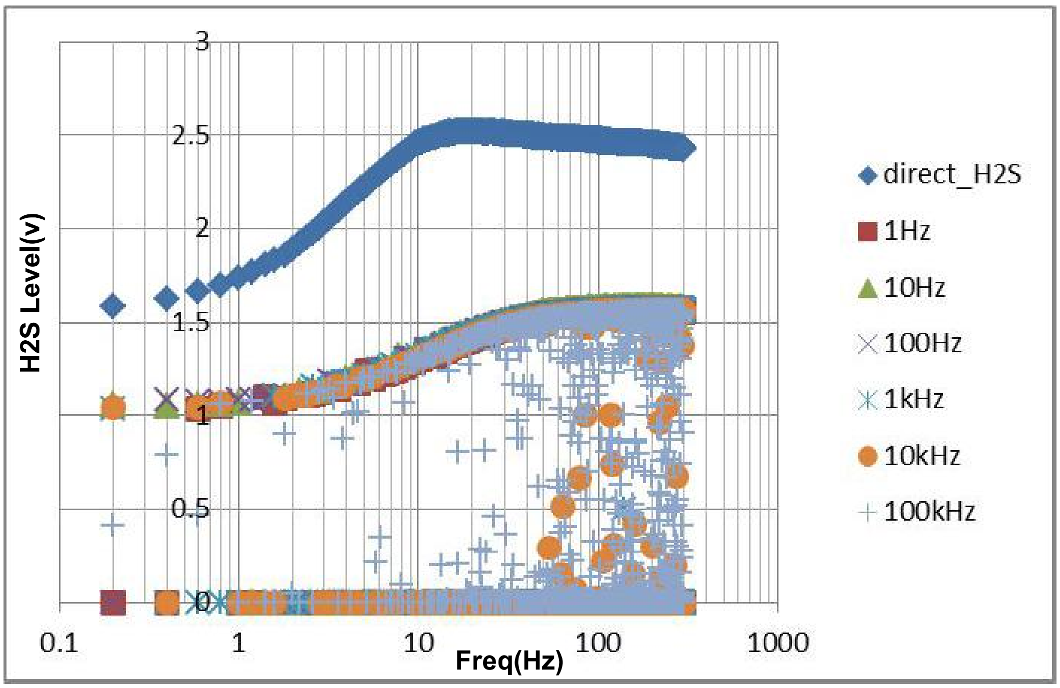

Figure 5.6: Graph of Hydrogen Sulfide against time over different frequencies.

Figure Figures 5.5, 5.4 and 5.6 show that the average energy of the waveform switching the gas sensor is proportional to the peak of the graph. We are interested in the peak of the graph, because Somov *et al.* [124] show that gas readings can be accurately deduced from the peak value of the gas sensor. Furthermore, the larger average energy of the waveform the more energy for the heating elements — [103][104][105] specify that the supply voltage must not be beyond 5V DC or AC for the heater and voltage of not more than 24VDC for the semiconductor.

Base on Figure 5.7 and 5.8 one can deduce that for run-to-halt (greedy) technique is best in heating the sensor, since it take shorter time compared to the switching technique. In order to double check our hypothesis, energy consumed over a wide range of frequency is investigated (see also: Figure 5.8) and it was found that it is slightly better to use direct heating than switching technique.

Finally, the we try to answer the question, "What is the optimum duty cycle for using 1KHz?". 1KHz is selected because it is midway between the best and the worst performance. This question is answered by 5.9 where 80% duty cycle seconds direct power (greedy technique). Looking at the chart one can see that direct heating is by far better than using any duty cycle, since it takes shorter time to complete the process. However, the time taken to heat the sensor at 80% is worth noting, because of the sharp drop. This is due the fact that the gas sensor act like a heat capacitor. The heat builds up with each cycle as long as the cycle is short enough to prevent the sensor from cooling.

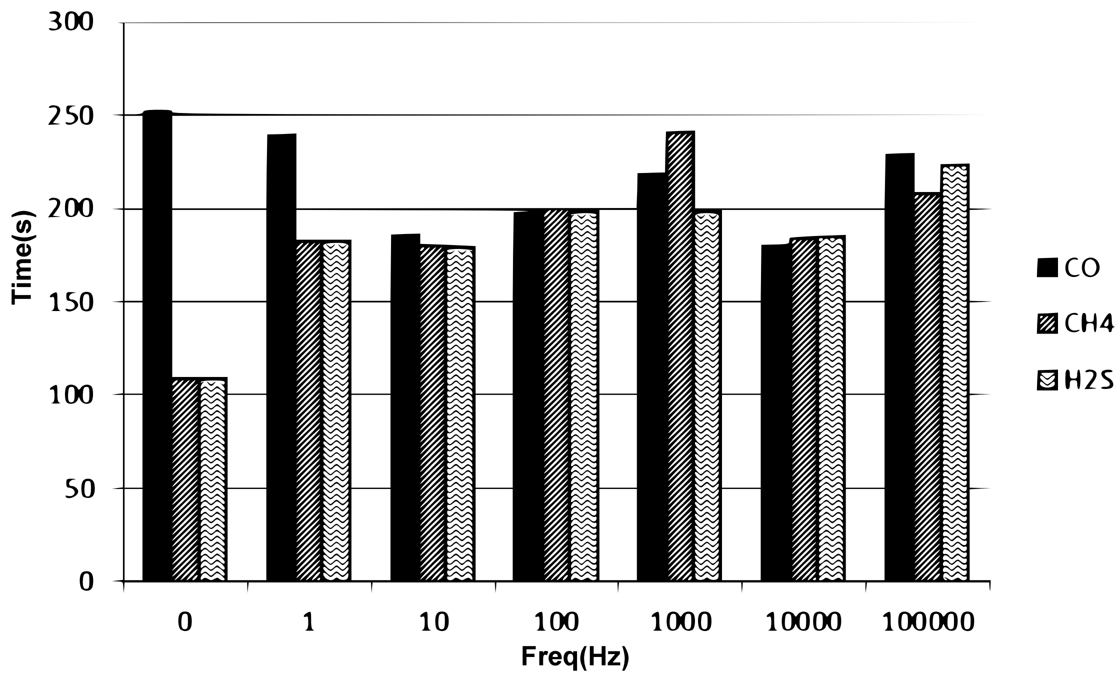

Figure 5.7: Graph of frequency against time taken for reading to reach peak value.

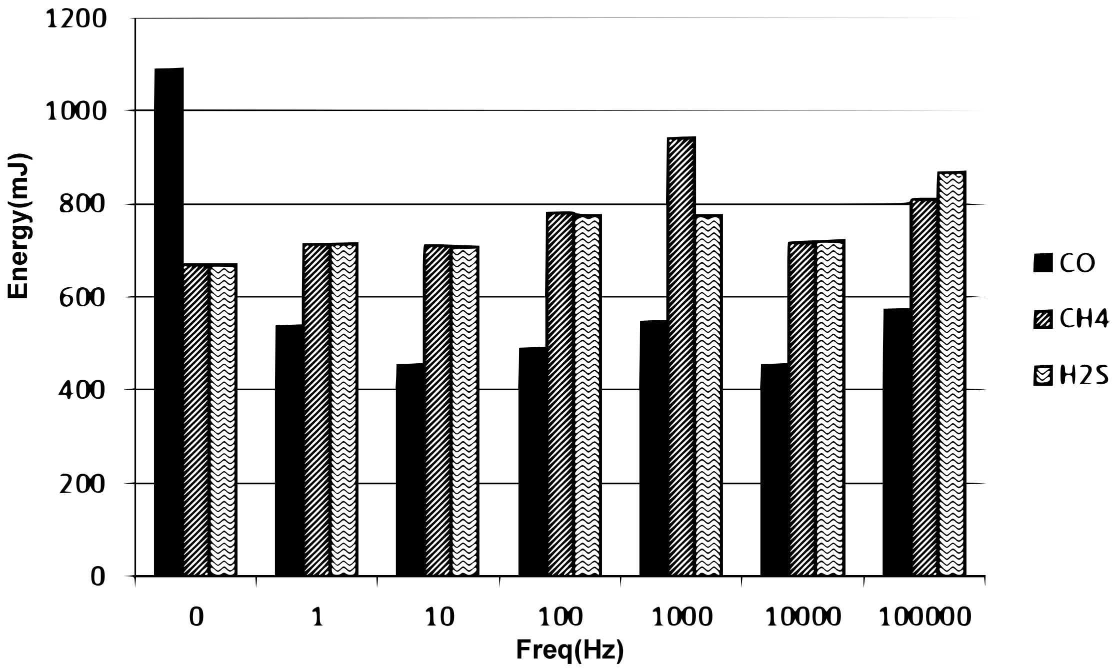

Figure 5.8: Graph of Frequency against energy required for gas reading to reach peak value.

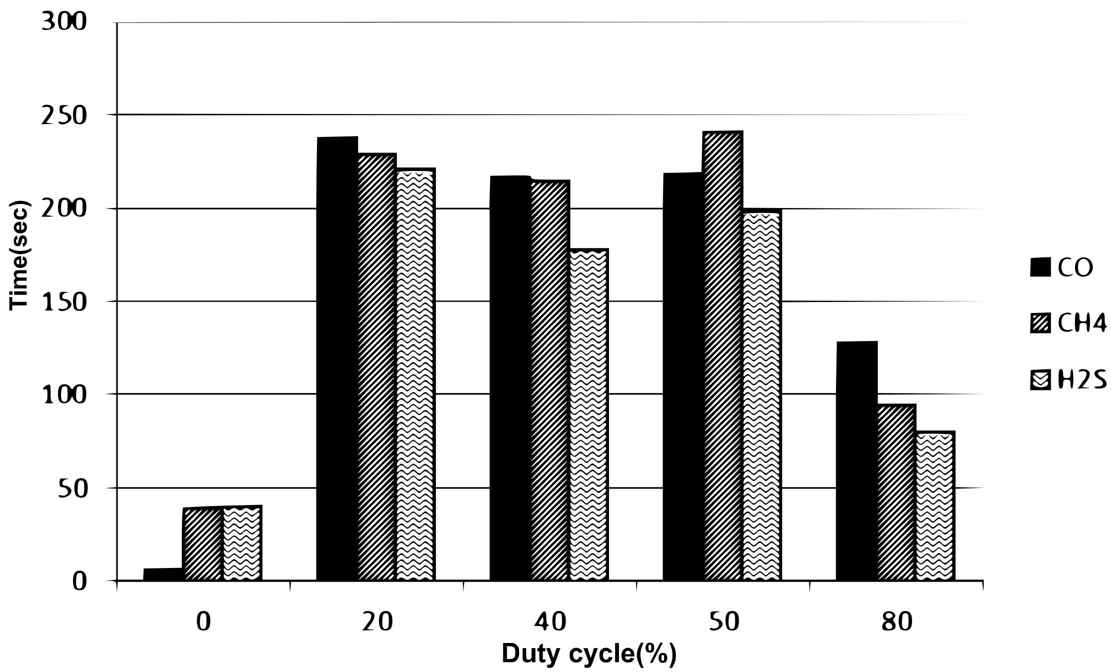

Figure 5.9: Graph of Duty cycle against time taken for reading to reach peak value.

5.4 System Testing

System test or end-to-end test, is a test carried out on the complete system to determine whether it complies with it's design requirement. Figure 5.10 shows the experimental setup. The electrical characteristic of the gas sensors are obtained from the datasheet [103][104][105] and their mathematical models are derived respectively. Equation 5.1, 5.2 and 5.3 are the derived models. These equations are used by the firmware to determine the concentration of gas in a given area.

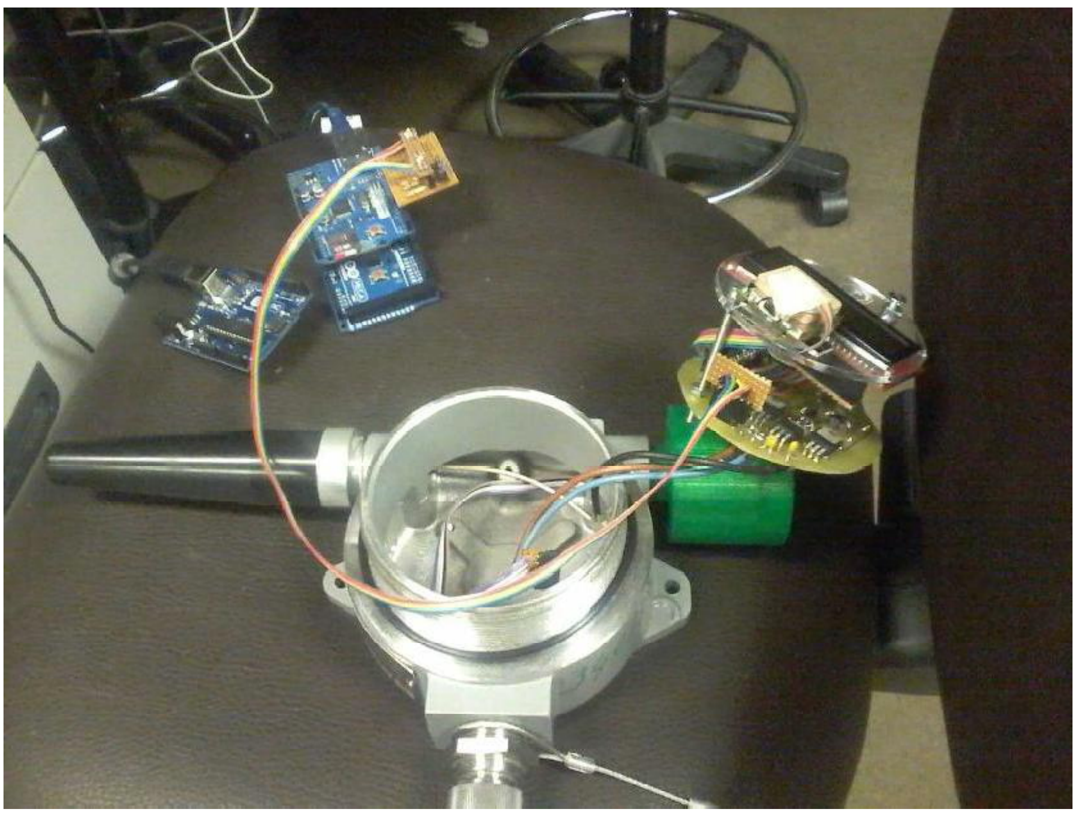

Figure 5.10: Setup for the system test.

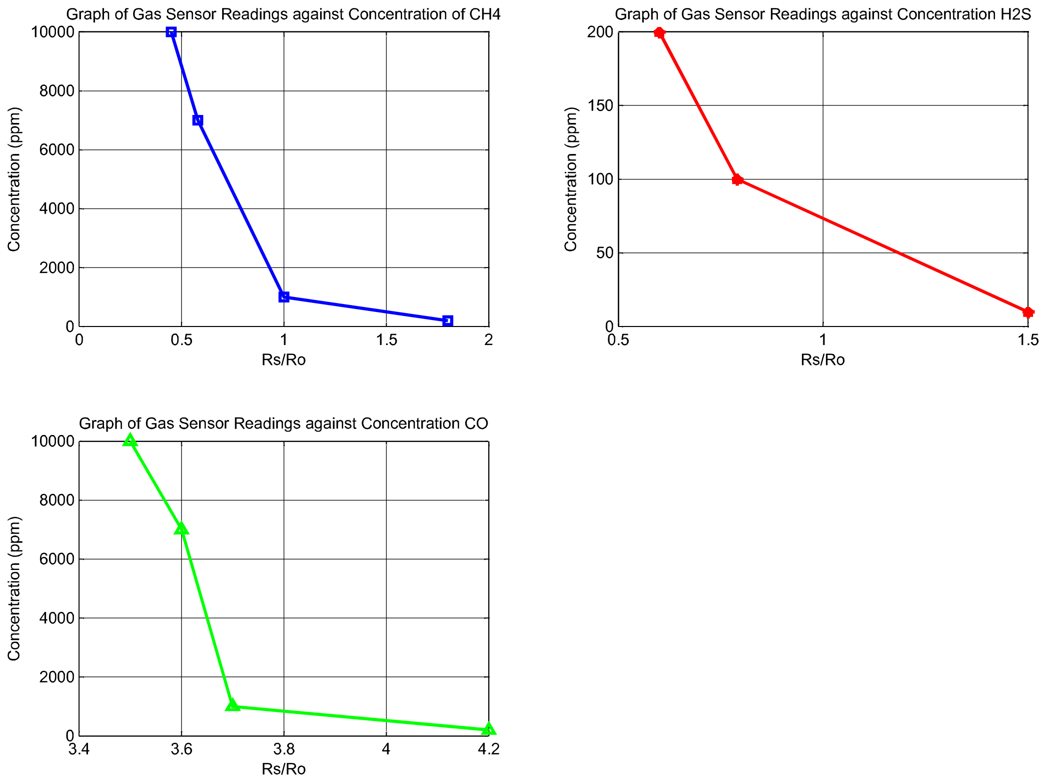

Figure 5.11: System behavior as shown in datasheet [103][104][105].

$$PPM_{CH4} = 7476.76e^{\frac{-2.0118R_s}{Ro}} \tag{5.1}$$

$$PPM_{CO} = 3.124 \times 10^{12}e^{\frac{-5.5886R_s}{Ro}} \tag{5.2}$$

$$PPM_{H2S} = 1473.62 \times e^{\frac{-3.3286R_s}{Ro}} \tag{5.3}$$

Furthermore, the graphs from the datasheets are used to obtain the Rs/Ro ratio show in Table 5.1, which is then used to calculate Rs. Rs is the resistance of the sensor, while Ro is a reference resistance given by the datasheet. It should be noted that Rs in this document is given in terms of voltage drop across the resistor instead of in Ohms. This is possible because the earlier and the later are directly proportional. The use of voltage drop allows us to easily derive the gas readings from the microcontrollers perspective as can be seen in the column, "*Digital equivalence of sensor*". These values are then copied to a memory card and inserted in an Arduino Ethernet shield which is connected to Arduino Mega2560 microcontroller. The microcontroller then reads the three values in each row and an provide equivalent analogue signal through its PWM ports (3, 5 and 6). The microcontroller reads new line when it receives signal from the gas sensor through the pin that it normally turns on the gas sensor's heaters in the actual system.

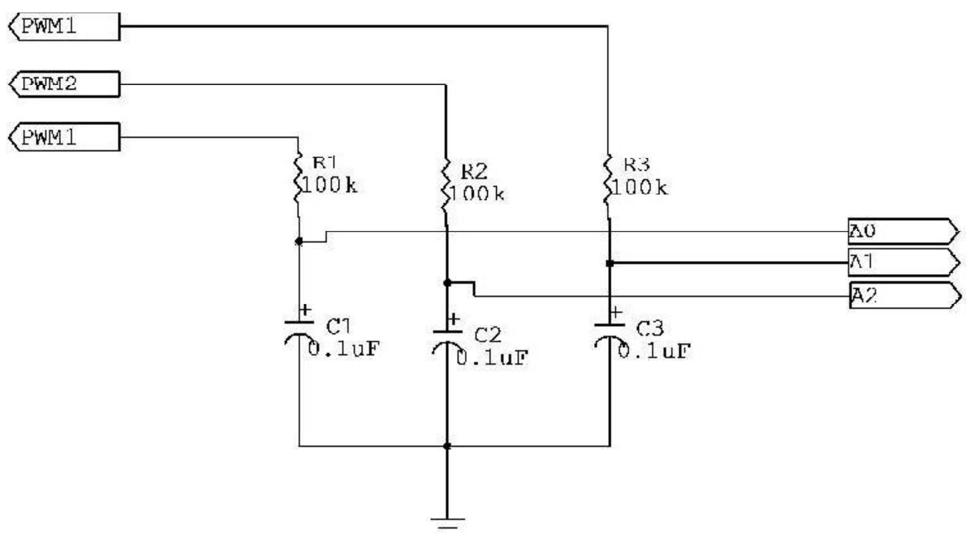

Figure 5.12: Filter circuit that simulates the gas sensors.

However, this technique has two main problems; the first is the fact that the PWM has 8bit resolution and the readings on the table (as well as the gas sensors ADC) has a resolution of 10bit. This problem is simply solved by dividing the read values by 4 before sending them to the PWM. Secondly, PWM is a pseudo-analogue entity. It gives the illusion of analogue readings by simply varying the width of rapid pulses as shown by the upper graph in Figure 5.13. This is a problem because the two microcontrollers have identical response time. Therefore, the receiver will see pulses rather than analogue values. To solve this problem a first order low pass filter with a very low corner frequency is developed (see also: Figure 5.12). The lower the frequency the higher the attenuation and the smoother the signal. By simulation using Circuit maker, we found that the smallest frequency with out completely losing the signal is 3% of the original signal (i.e $489 \times 3\% \approx 15Hz$). The resulting signal can be seen in the lower graph of Figure 5.13.

$$
\begin{aligned}
f_c &= \frac{1}{2\pi RC} \\
15 &= \frac{1}{2\pi RC} \\
R &= \frac{1}{2\pi 15 \times C} \\
Choosng \quad C &= 0.1\mu f \\
R &= \frac{1}{2\pi 15 \times 0.1 \times 10^{-6}} \\
&\approx 100,000\Omega
\end{aligned}
\tag{5.4}
$$

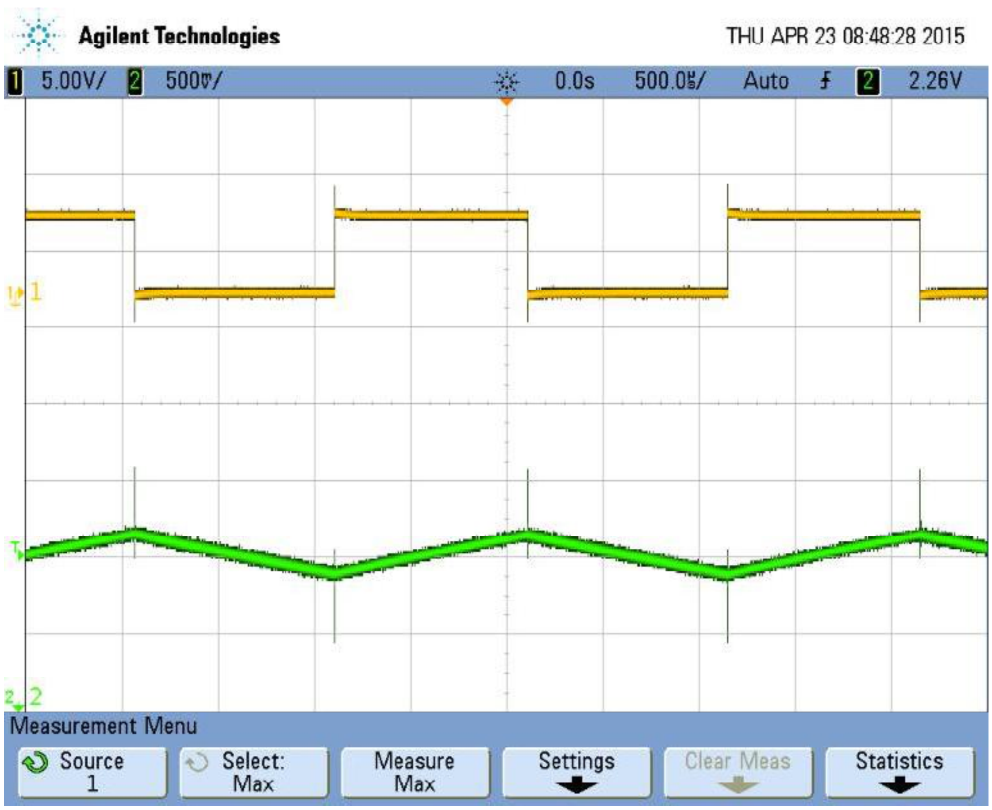

Figure 5.13: PWM reading before and after passing through a first order low pass filter.

Table 5.1: Readings obtained from system test.

Gas level (ppm)			Gas level in ratio (Rs/Ro)			voltage drop across sensor (Rs)			Digital equivalence of sensor (Rs)			Readings from gas sensor (Rs)			Readings from gas sensor (ppm)		
CO	H2S	CH4	CO	H2S	CH4	CO	H2S	CH4	CO	H2S	CH4	CO	H2S	CH4)	CO	H2S	CH4
0	0	0	5	2	2.5	1.5	3	1.75	307	614	358	303	600	353	3	2	55
10	0	0	5	2	2.5	1.5	3	1.75	307	614	358	303	599	353	3	2	54
200	0	0	4.2	2	2.5	1.26	3	1.75	258	614	358	257	600	353	223	2	54
1000	0	0	3.7	2	2.5	1.11	3	1.75	227	614	358	226	600	353	3822	2	54
0	10	0	5	1.5	2.5	1.5	2.25	1.75	307	461	358	304	453	353	3	11	54
0	200	0	5	0.6	2.5	1.5	0.9	1.75	307	184	358	304	601	353	3	196	53
0	0	0	5	2	2.5	1.5	3	1.75	307	614	358	304	601	353	3	2	54
0	0	10	5	2	2.5	1.5	3	1.75	307	614	358	304	601	353	3	2	53
0	0	200	5	2	1.8	1.5	3	1.26	307	614	258	304	601	257	3	2	206
0	0	1000	5	2	1	1.5	3	0.7	307	614	143	304	601	145	3	2	986
0	0	0	5	2	2.5	1.5	3	1.75	307	614	358	303	601	353	3	2	53

In a nutshell, it can be seen that there is correlation between the readings from the sensor node and the readings from the emulator, except where the gas readings 0ppm are expected. This is due to the fact that exponential functions only reach zero at infinity. To solve this error, we made an "*if*" statement that turns any value lower than 3, 2 and 55 to zero for the sensors CO, H_2S and CH_4 respectively.

Finally, an experiment is carried out to measure the energy harvesting behaviors of the gas sensor. In this experiment, the gas sensor is is connected to two solar panels of +12v 10W each and a +12v battery as shown in Figure 5.14. The system is allowed to run for twenty eight hours. An Arduino mega2560 is used to measure the battery level which is an energy consumption indicator.

Figure 5.14: Setup for the harvesting experiment.

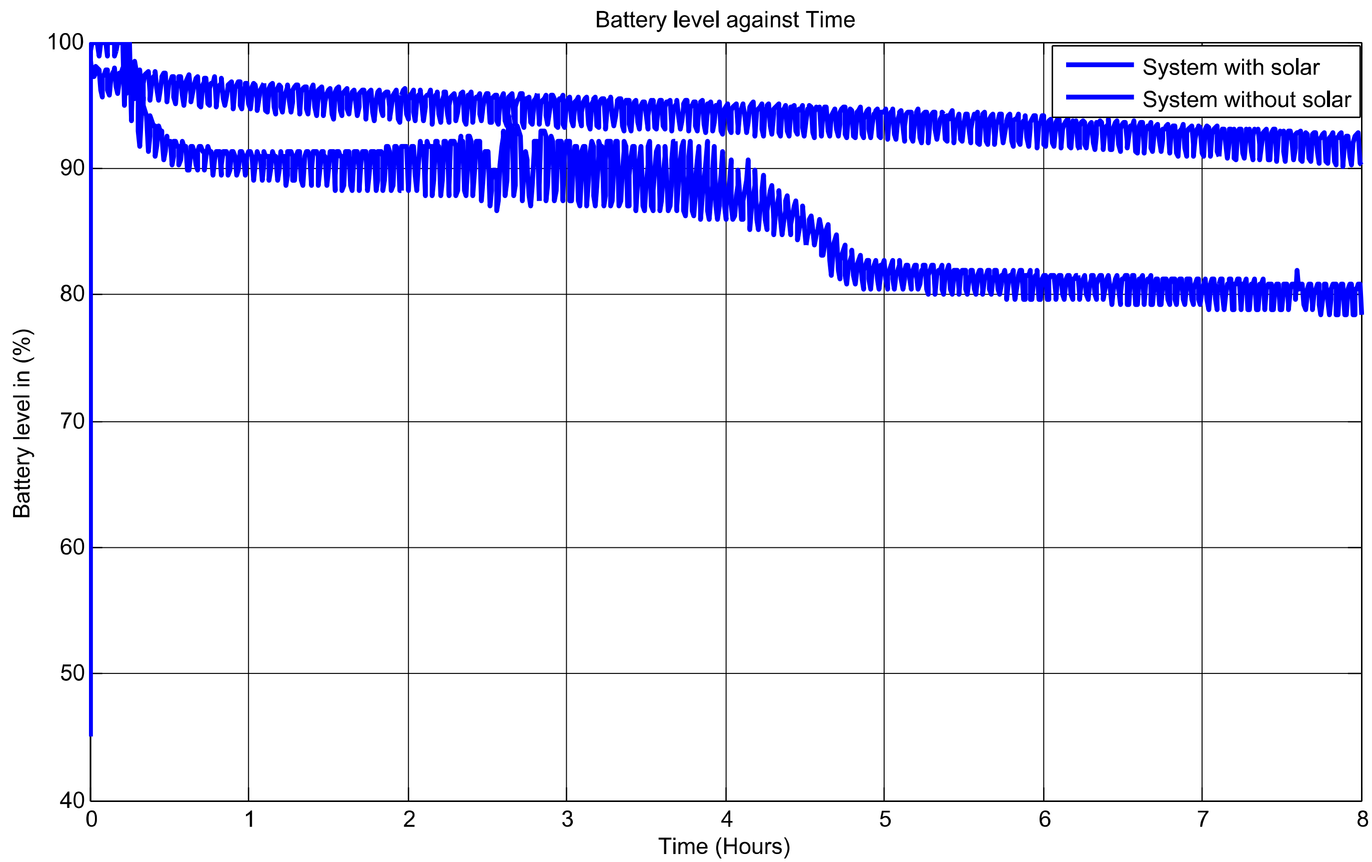

Figure 5.15: Comparison of battery energy consumption and solar energy consumption.

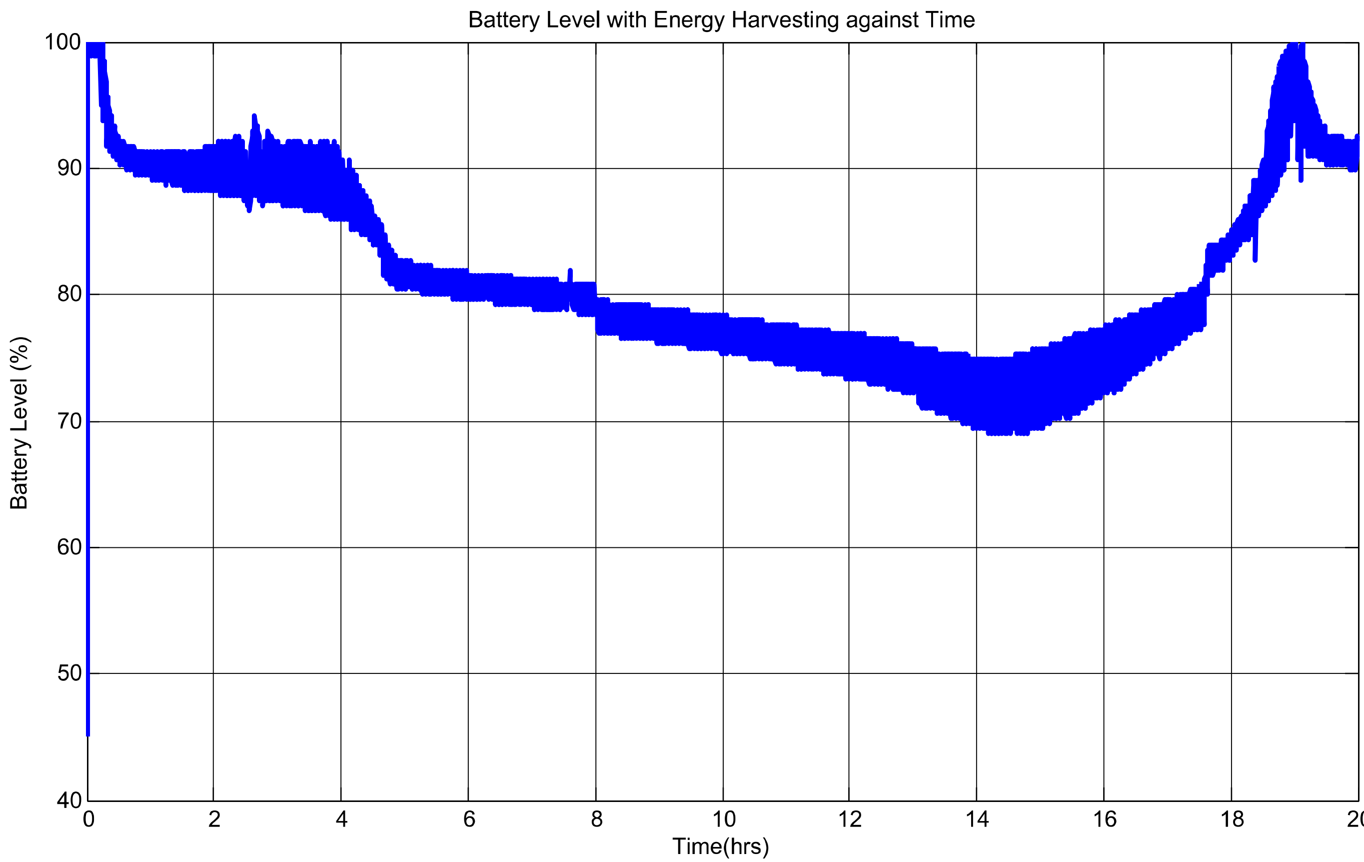

Figure 5.16: Solar performance over long period of time.

Figure 5.15 shows the battery energy consumption with solar and the battery consumption carried out indoors without solar over eight hours starting from 12:00 noon. A sharp sudden drop in voltage is seen in the battery with solar, this is due to heat from the environment. Generally batteries performance falls with rise in temperature [125]. The battery without energy harvesting can be seen to loose energy linearly, with a lost of about 10% per 8hrs. This is consistent with the manufacturers specification [125].

Twelve more hours were added to the energy harvestig setup. The experiment stopped because the Arduino measuring the battery level of the system ran out of battery. The Arduino's is identical to the battery in use by the gas sensor. Figure 5.16 shows the battery level from 12.00PM to 8:00AM in the morning. It can be seen that around 4.00AM when the sun started rising the battery is beginning to get charged by the solar system until around 8.00AM when the environment starts to get warm. The battery is allowed to charge while the solar panel takes over with powering the system due to Millmans theorem [112]. The voltage level of the solar pane can be seen in Figure 5.17. The only problem with this technique of energy harvesting is dust which gradually covers the panels.

The ambient temperature is also affects the gas sensors. Figure 5.19 shows how the readings of the gas sensor change at 3.00PM. At this time the temperature in the container of the gas sensor has risen due to cumulative heat that started at sunrise. However as the environment cools the error drop falls with fall in ambient temperature.

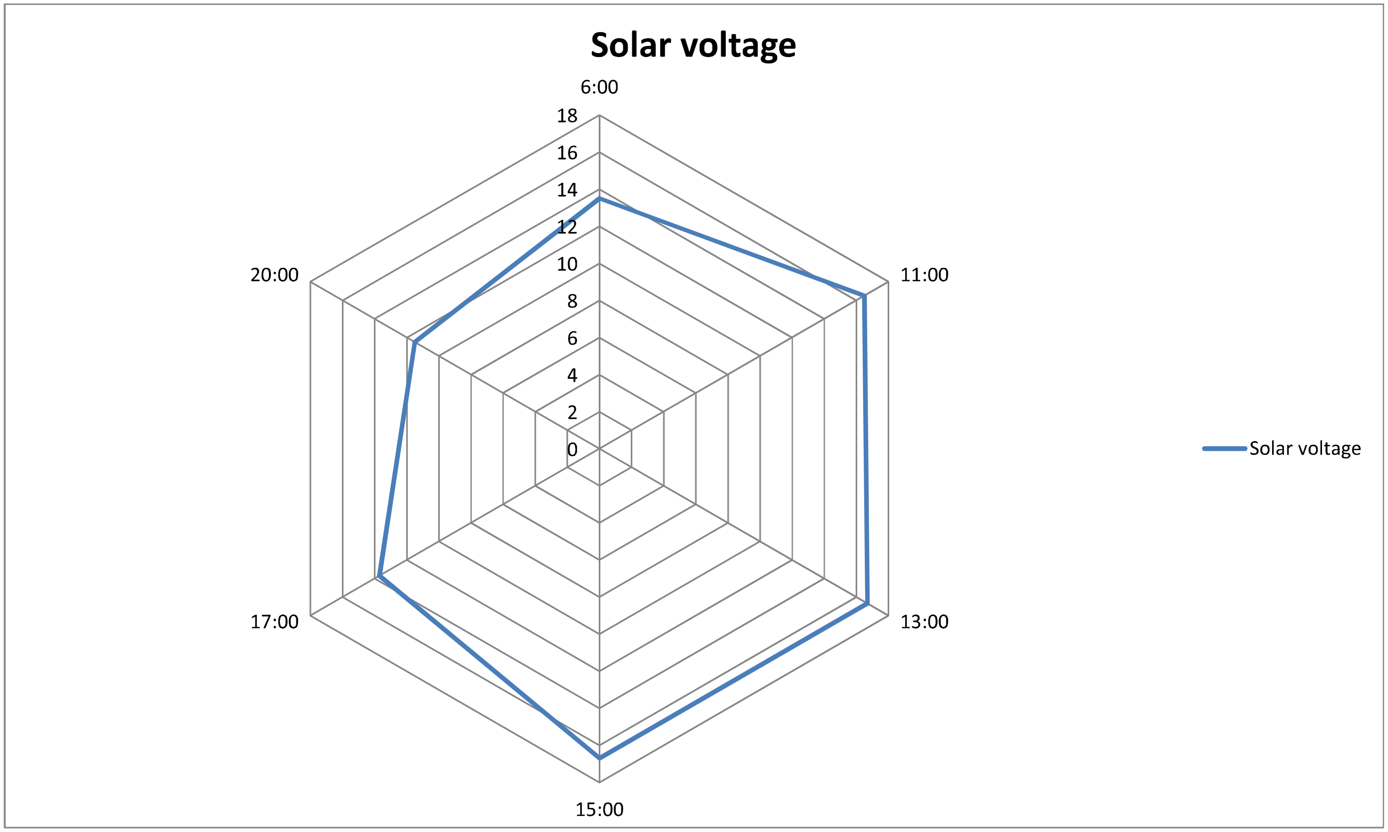

Figure 5.17: Setup for the harvesting experiment.

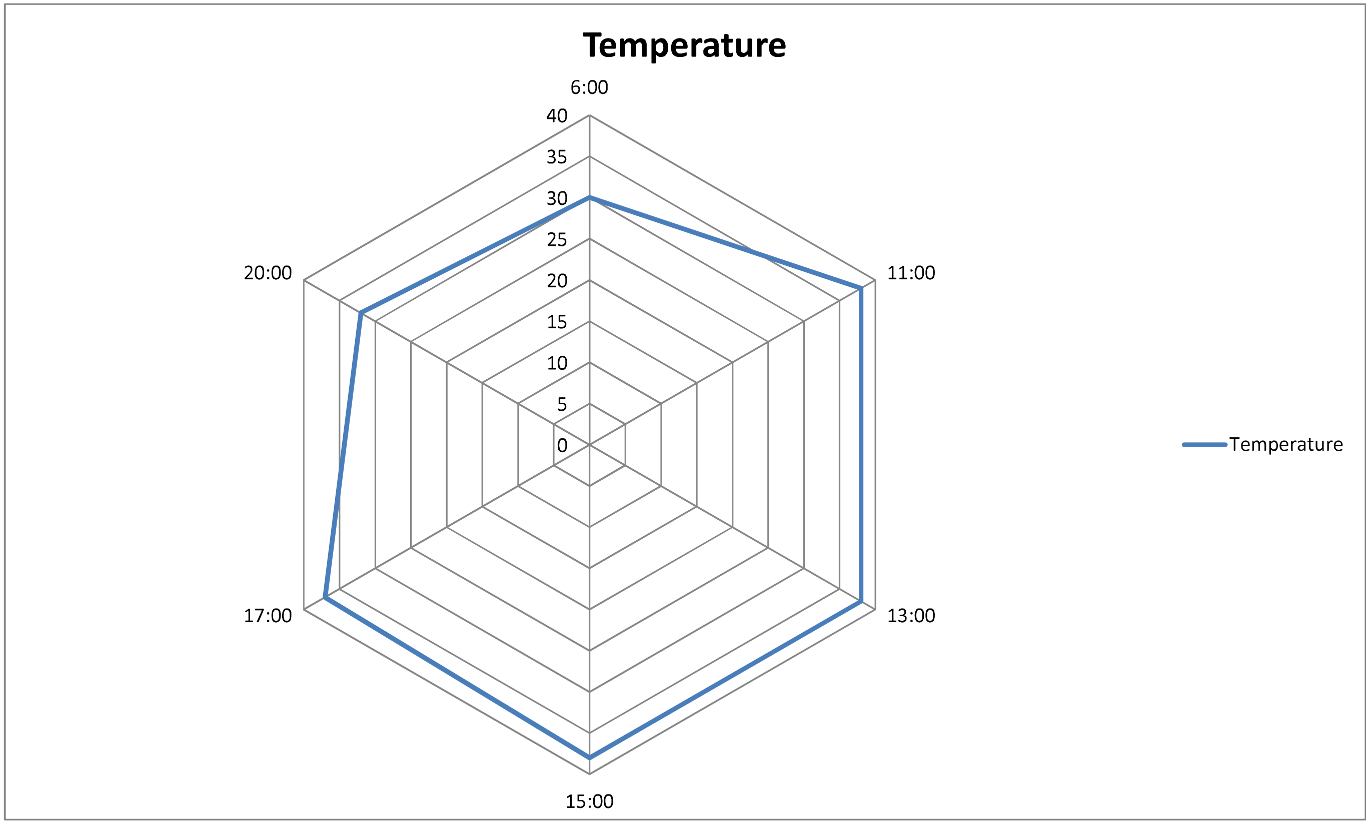

Figure 5.18: Ambient temperature in degree Celsius over 24 hours.

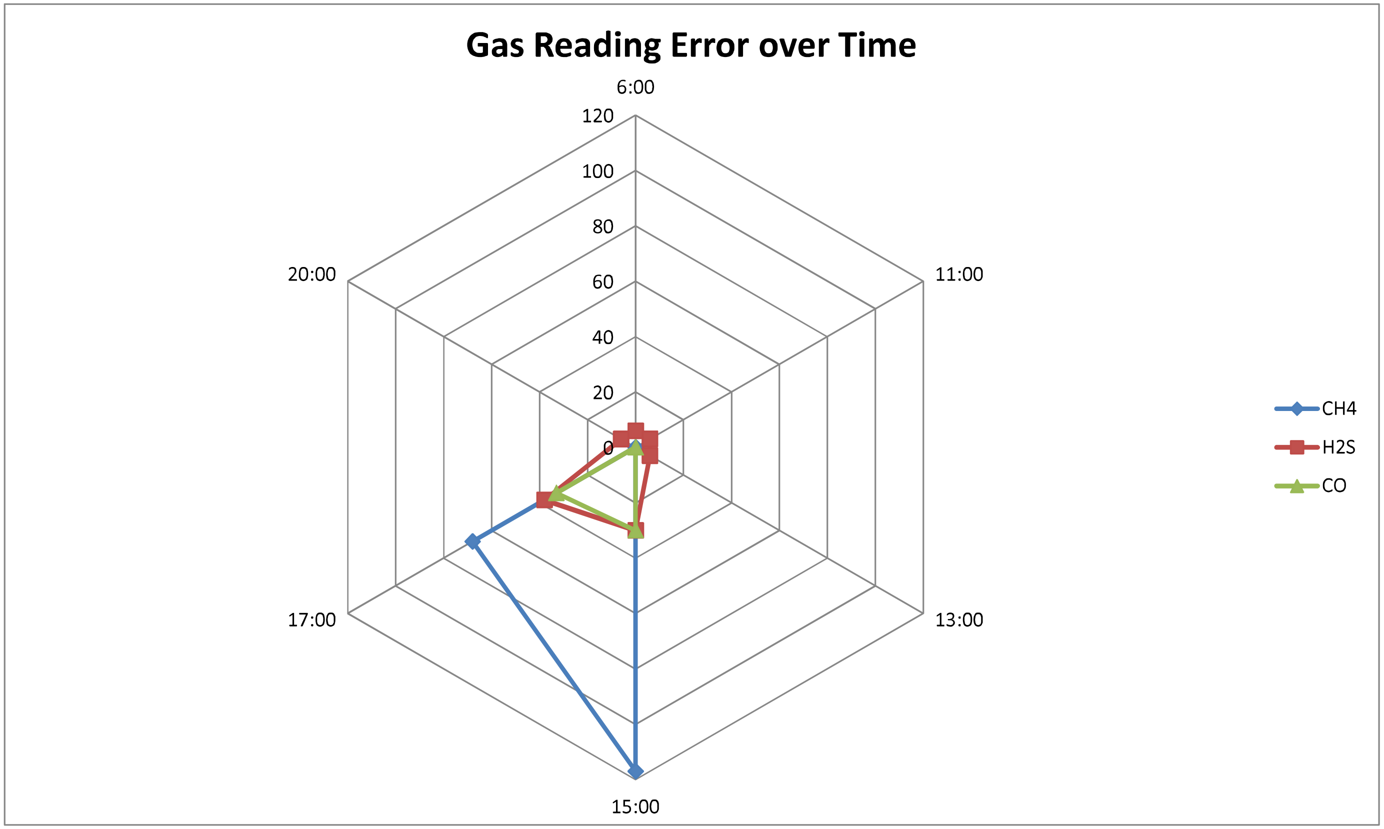

Figure 5.19: Error in gas reading due to ambient temperature.

5.5 Summary

This chapter has investigated that the gas sensor encompasses about 66.8% of the total energy consumption of the sensor node and that the best technique to sensor reading is direct heating for atleast 1min (as also specified by the datasheets [103, 104, 105]) followed by using 80% duty cycle at 1kHz. It is worth investigating to check whether this repeated heating method has any effect on the molecular structure of the semiconductor. Furthermore, other factors such as ambient temperature also affect the system. This problem can be solved by using a thermistor which will provide feedback to the system so that it can autonomously correct the error.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This document has proposed a sensor network developed on top of Zigbee protocol. The system consists of a Gas sensor, an actuator, a relay node and finally a coordinator node. The gas sensor is an end node responsible for sensing the environment. The sensor node sounds an alarm and reduces its sleep cycle when there is gas leakage and lengthen its sleep period when there is no gas leakage. In other words, the sensor node adapts to the level of toxic and combustible gas (especially CO, CH_4 and H_2S) in the atmosphere. The actuator is another end node that is used in turning on and off valves. Due to the fact that the actuator has abundant supply of energy there is no need for sleep cycles. The relay node is responsible for moving data from one node to another. Finally the coordinator is a full function device (FFD) that is responsible for gathering data and overseeing the activities of the network. As such the coordinator must have abundant source of power and cannot go to sleep.

The aim of the proposed system is to sense gas leakage, alert people within the vicinity and periodically report gas leakage to the coordinator. Although there are many of such systems in the market, they are often associated with unnecessary difficulties in installation and management. This is why we set out to develop an easy to use system that does not require any technical training before use.

Chapter 4 presents detailed design of the proposed system, while chapter 5 reports the experiments carried out to test and evaluate the system. Findings from this tests have shown an energy aware gas sensing can be developed over Zigbee at a cheaper rate than WSN solutions presently available in market. The system has an easy to use application and a plug-n-play sensor nodes with whom users require no extra training or certification. If this technique is given more attention, these cheap sensor nodes will replace the complex sensors currently in market.

6.1.1 Limitations

Although the system has shown many promising results, it has some limitations in its functionality. Some of this limitations are;

1. The Sensor node is equipped with both GPS device and a Xbee wireless module, both devices require UART port to function properly. Unfortunately,

Atmega328p has only one UART port. Furthermore, the microcontroller has no Pin-change interrupt pins. For this reason, software serial cannot receive data but can transmit. Since the GPS serves as an input device, while the Xbee is an output one. The GPS is connected to the UART while the Xbee is connected to Pin16 and Pin17 for input and output respectively. As such the gas sensor is a simplex device.

2. Change in temperature of the environment seriously affects the accuracy of the gas sensor and the Lead-Acid battery used for energy harvesting.

6.2 Recommendation

From the readings in the experimental section it is found that the CO gas sensor has more sensitivity compared to the other three. Therefore it can be used alone to sense the environment and empirical formula could be derived for calculating the gas reading of the three other gasses. The other two can then be turned on for selectivity sake only. A temperature sensor is also recommended so as to allow the system correct the deviation in gas reading due to rise in temperature. Moreover, energy harvesting can be added to the relay nodes. The relay nodes can then be placed in twos so that when one is harvesting energy the other is can cover for him. This will ensure longer life for the network and flexibility.

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APPENDIX A

TESTING

Introduction

Testing is the process of investigating the efficiency or how well a system conforms to its design requirements. This section provides reader with information on how the system was tested, problems encountered and how they were solved. This section comes in handy when one wants to reproduce or improve the system and found one's self stuck in similar problem(s) presented herein. All codes used in testing the different modules of the proposed system can be made available upon request in the folder titled "*Tests*"

Testing Microcontroller

The microcontroller can be programmed in two ways: 1) It can be programmed through conventional techniques — that is by using Assembly language or Embedded C. Although these methods allow the program direct access to the microcontroller, they also require a micorcontroller-programmer and development time is relatively long. 2) Arduino language. Arduino language is simply C++ programming. Once the programmer has finished writing his/her program, the Arduino IDE compiles the code to suit the microcontroller intended. This is achieved through the use of some header files and libraries. The advantages of using Arduino language is:

1. It provides the programmer with variety of code snippet. Thereby reducing development time.

2. Programming can be done through the use of Arduino board. Hence the programmer requires no extra microcntroller-programmer.

Since we are using Atmega328p Arduino Uno, which uses the same microcontroller is used to program the microcontroller. Using this technique led us to some problems: The microcontroller requires needs a bootlaoder in order to run Arduino language. The process of burning this bootloader is available in `http://www.arduino.cc/en/Tutorial/ArduinoToBreadboard`. Another issue is that the pinout of the microcontroller has an entirely different nomenclature when programming with Arduino. Therefore, one needs to map the new pin names to the original names of the pins in order to program the right pins. Table A.1 maps the pins of Atmega328 to the Arduino's nomenclature.

Table A.1: Mapping pin names to Arduino programming

Microcontroller	Arduino
1	reset
2	0
3	1
4	2
5	3
6	4
11	5
12	6
13	7
14	8
15	9
16	10
17	11
18	12
19	13
23	A0
24	A1
25	A2
26	A3
27	A4
28	A5

Testing xBee

Algorithm 2 and 3 were used to test the xBee S2B Pro transceiver. It was noticed that the module does not transmit with Atmega328p but works fine with Arduino shield. It was discovered that Xbee module is powered by 5v instead of 3.3v. Another test is carried out after LM317 is configured to power the tranceiver at 3.3v as shown in Subsection B of Appendix B. In this second test, the xBee records huge packet loss, those that made it were found to be in error. The problem was later discovered to be level mismatch between Atmega328p and xBee. The level converter as shown in Figure A.1.

Finally, it was discovered that the Xbee transceiver and the Atmega328p are

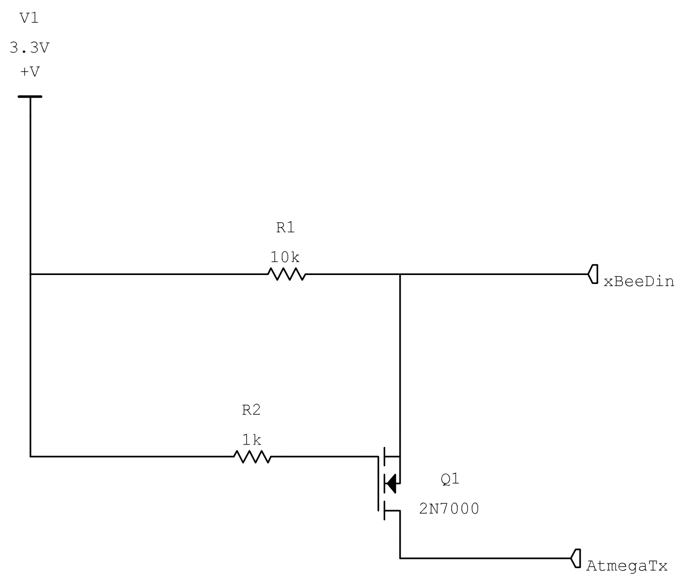

Figure A.1: A circuit diagram of 5v to 3.3v level converter

on the same side of the board were soldering should take place. To solve this problem ICs should always be flipped when placed on the PBC software, so that the IC is placed at the opposite end of the solder.

Testing GPS

The GPS module uses software originally developed by Mikal Hart. The application sends "*National Marine Electronics Association (NMEA)*" sentences to the GPS and receives replies out of which the desired information is extracted. For more information about NMEA sentences please refer to `http://www.gpsinformation.org/dale/nmea.htm`. The functions were tweaked such that only longitude, latitude, date and time are collected. The collected in formation is converted to string of the format, "26.305676,50.146324,0/0/2000,20:8:8".

The testing was took place outdoors in order to ensure speedy synchronization between the GPS module and the GPS satellites. The string of information is passed to the function ”*sendThis*” in Algorithm 2. The only problem encountered with the GPS is its refusal to send intelligent data to the Xbee module at the receiver side. This problem was sovled by converting the data in to string before sending to the receiver.

Algorithm 2 Source code for testing xBee

```
#include <SoftwareSerial.h>
#include <String.h>
SoftwareSerial ss(10, 9);
int isWakeXbee = 12;
int WakeXbee = 11;
int sendThis (String msg);

void setup() {
ss.begin(9600);
Serial.begin(9600);
 pinMode(isWakeXbee, INPUT); //sleep state output pin
 pinMode(WakeXbee, OUTPUT); //sleep pin
 digitalWrite(WakeXbee, LOW); //wake node
}

void loop() {
 // put your main code here, to run repeatedly:
 String myMsg = ”Alhamdulillah”;
 int resp = sendThis(myMsg);
 Serial.println();
 Serial.print(resp);
 delay(1000);
}

int sendThis (String msg){
 long sum = 0; //sum of all bytes after length byte for checksum
 int i=0; //payload counter
 digitalWrite(WakeXbee, LOW);

 while (msg[i]){ //counting payload size which is needed for offset 1-2
 sum += msg[i];
 i++;
 }
```

Algorithm 3 Source code for testing xBee continued

```
sum += 0x10 + 0x01 + 0x00 + 0x00 + 0x00 + 0x00
    + 0x00 + 0x00 + 0x00 + 0x00 + 0xFF + 0xFE + 0x00 + 0x00;
ss.write(0x7E); //0. Delimiter
ss.write((byte)0x0); //1. length of payloads A
ss.write(i+14); //2. length of payloads B counted below
ss.write(0x10); //3. Frame type Count=1
ss.write(0x01); //4. Frame ID Count=2
ss.write((byte)0x0); //5. 64bit Destination Address Count=3
ss.write((byte)0x0); //6. Count=4
ss.write((byte)0x0); //7. Count=5
ss.write((byte)0x0); //8. Count=6
ss.write((byte)0x0); //9. Count=7
ss.write((byte)0x0); //10. Count=8
ss.write((byte)0x0); //11. Count=9
ss.write((byte)0x0); //12. Count=10
ss.write(0xFF); //13. 16bit Destination Address Count=11
ss.write(0xFE); //14. Count=12
ss.write((byte)0x0); //15. Set to maximum number of hops Count=13
ss.write((byte)0x0); //16. Tx option Count=14

//Txing fram payload
i=0;
while (msg[i]){
ss.write (msg[i]);
i++;
}
ss.write(0xFF - (sum & 0xFF)); //checksum
i=0;
int response=-1; //-1 indicates error
while (ss.available()){
Serial.println(ss.read(), HEX);
i++;
if (i==7)
response = ss.read();
}
return (response);
}
```

Testing Gas Sensor

Algorithm 4 is used to test the the gas sensor. A lighter was used to to test the gas sensors. The gas was let out of the lighter and the voltage level were observed through the serial terminal of the Arduino Integrated Development Environment (IDE). The only problem encountered here is the connection of the gas sensor which was with the help of the datasheet.

Algorithm 4 Pseudocode to Gas Sensor test

For(int i=0; i¡40; i++){
  $Val_{H2S} \leftarrow Val_{H2S} + A_0$
  $Val_{CO} \leftarrow Val_{CO} + A_1$
  $Val_{CH4} \leftarrow Val_{CH4} + A_2$
}
$Val_{H2S} \leftarrow \frac{Val_{H2S}}{40}$
$Val_{CO} \leftarrow \frac{Val_{CO}}{40}$
$Val_{CH4} \leftarrow \frac{Val_{CH4}}{40}$
Serial.print($Val_{H2S}, Val_{CO}, Val_{CH4}$)

Standalone Application

An application that collects information from the network through the coordinator and save it in a database is developed (see also: Figure A.2). The application collects information from the coordinator through serial port. For the sake of ease of development the application was implemented using Visual Basic .Net. For more details on the application refer to Chapter 4 of this document.

The software is tested by running it along side the sensor node. As can be seen in Figure A.2, the GPS information is used to locate the sensor on Google Maps and it corresponding gas reading are shown below. One problem was encountered with the software; most of the information transmitted is lost during first transmission. To solve this issue, the coordinator was connected to the computer through Arduino Uno microcontroller instead of direct connection. The microcontroller captures the data as soon as the coordinator sends it and it then repeats the data until the standalone application sends a signal that it has received the information.

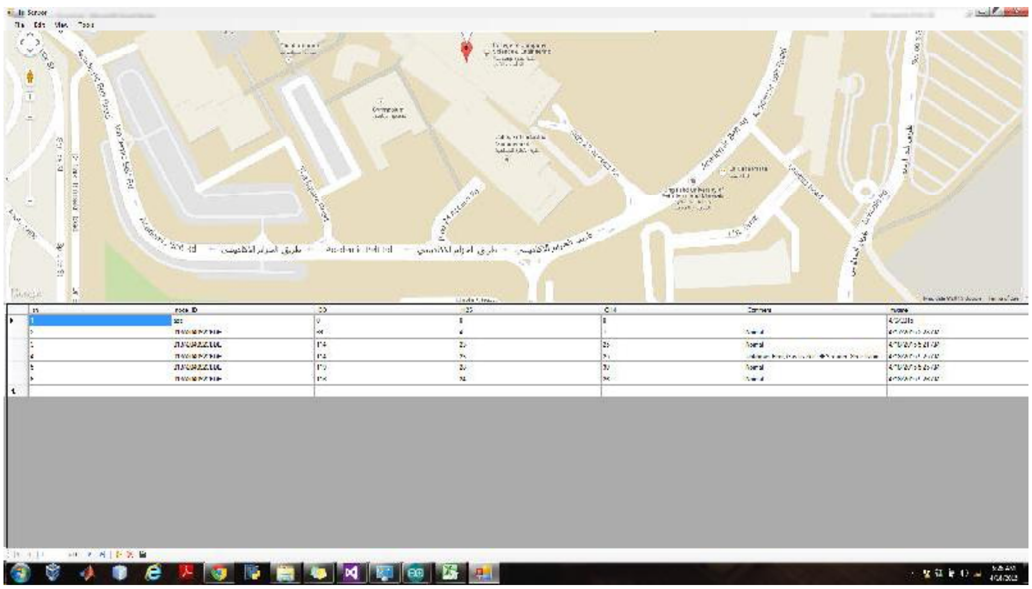

Figure A.2: Standalone Application that collects information from the network and save it in a database.

APPENDIX B

POWER SUPPLY DESIGN

Introduction

Given the fact that we used ready made power supply for our wireless actuator, we find it important to give readers a design of a power supply in case he wants to make one for his system. Although the power supply in this section is designed with safety of the user in mind, the user is urged to take extra precautions while working with the Mains, for it incur deadly repercussions.

Figure B.1 is a block diagram showing how alternating current (AC) is converted to direct current (DC) which can then be used to power digital circuits. The Transformer section is steps down the power to a lower voltage level. The step downed AC is the fed to a Rectifier where it is converted to direct current. However, at this stage the DC ripples between 0v and the transformer's step downed voltage. This ripple is not good for powering digital circuits. Therefore, the ripple has to be Filtered. Albeit filtering, the ripple is still present and voltage may fall

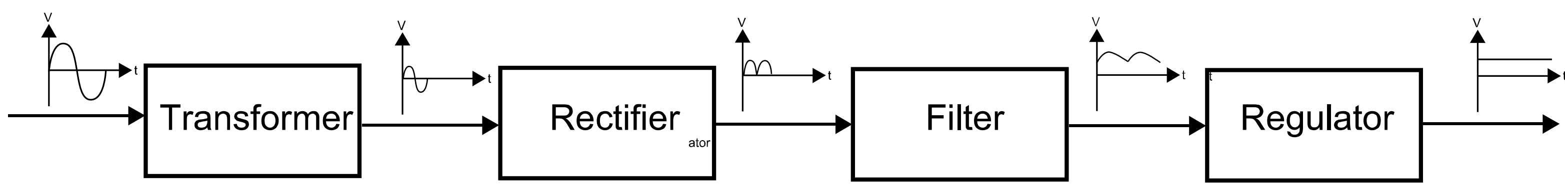

Figure B.1: A block diagram for power supply with increase in load. To solve these problems, a regulator is used.

Note that the presented block diagram in Figure B.1 is not power supply arrangement. For example, some designs have a Filter-Transformer-Rectifier-Filter-Regulator arrangement. The first filter is a high-pass filter that allows AC voltage of about 40kHz to pass, this ensures transformers with small form factor (size) as the size of transformers reduce with increase in frequency.

Power Supply Unit

This section will present user with the design of a power supply using the block diagram above. The reason being that it is to our best belief that this power supply is the safest compared to its small and more efficient counter parts.

Transformer

$$I_{xbee} = 205mA \tag{B.1}$$

$$I_{Atmega} = 50mA \tag{B.2}$$

$$I_{relay} = 33mA \tag{B.3}$$

$$\begin{aligned} I_{Total} &= I_{xbee} + I_{Atmega} + I_{relay} \\ &= 205 + 50 + 33 \\ &= 288mA \end{aligned} \tag{B.4}$$

The maximum possible current (I_{Total}) consumed by the wireless actuator is

288mA. Therefore, a 9v, 300mA output transformer is selected for the power supply.

Rectifier

The greatest concern in designing a rectifier is the voltage dropped across the diodes in reverse bias mode. This reverse voltage is known as *Peak Inverse Voltage* (PIV).

$$PIV = 2V_{max} \tag{B.5}$$

$$Vmax = V_{rms} \times \sqrt{2} \tag{B.6}$$

$$\therefore PIV = 2V_{rms} \times \sqrt{2}$$

$$= 2 \times 9 \times \sqrt{2}$$

$$= 25.94v$$

Therefore, the diodes have to be greater than 25.49v and 300mA. Hence, 1N4001 was chosen.

Filter

$$Ripple factor = \gamma = \frac{1}{(4\sqrt{3} \times f \times R_L \times C)} \tag{B.7}$$

$$Where;$$

$$R_L = \frac{V_o}{I_o} \tag{B.8}$$

$$I_o = output \quad current \quad from \quad the \quad power \quad supply \tag{B.9}$$

$$V_o = Power \quad supplys \quad output \quad voltage \tag{B.10}$$

$$C = Shunt \quad capacitors \tag{B.11}$$

$$\therefore R_L = \frac{5}{(300 \times 10 - 3)}$$

$$\approx 16.7\Omega$$

$$Choosing \quad \gamma = 20\%$$

$$0.2 = \frac{1}{(4\sqrt{3} \times 50 \times 16.7 \times C)}$$

$$C = 866.02 \times 10^{-6}$$

$$\approx 1000\mu f$$

$$V_c = V_{max}1.4 \tag{B.12}$$

$$= 9 \times \sqrt{2}1.4$$

$$= 11.33v$$

Therefore, we need a capacitor of $1000\mu f$, 25v (ie greater then 11.33v).

Regulator

$$V_{in} = V_c - 2V_{rp} \tag{B.13}$$

$$\begin{aligned} V_{rp} &= \frac{I_{dc}}{4 \times f \times C} \\ &= \frac{(300 \times 10^{-3})}{(4 \times 50 \times 1000 \times 10^{-6})} \\ &= 1.5v \end{aligned} \tag{B.14}$$

$$\begin{aligned} \therefore V_{in} &= 11.331.5 \\ &= 9.83v \end{aligned}$$

Since $V_{in} > 5v$ the regulator 7805 will successfully work. The regulator 7805, as the name implies, provides 5v regulated power supply but the Xbee transceiver needs 3.3v to function properly. Therefore we need another regulator to power the transceiver. Due to scarcity of 3.3v fixed regulators *LM317* is selected.

$$V_o = 1.25(1 + \frac{R_2}{R_1}) + I_{ADJ} \times R_2 \tag{B.15}$$

$Where;$

$$V_o = Targeted \quad output \quad voltage = 3.3v \tag{B.16}$$

$$I_{ADJ} = 100\mu A \tag{B.17}$$

$$R_1 = 240\Omega \quad (recommended \quad by \quad datasheet) \tag{B.18}$$

$$\begin{aligned} 3.3 &= 1.25(1 + \frac{R_2}{240}) + (100 \times 10^{-6}) \times R_2 \\ R_2 &= \frac{(3.3 - 1.25)}{((1.25 \times 240) - (100 \times 10^{-6}))} \\ &\approx 430\Omega \end{aligned}$$

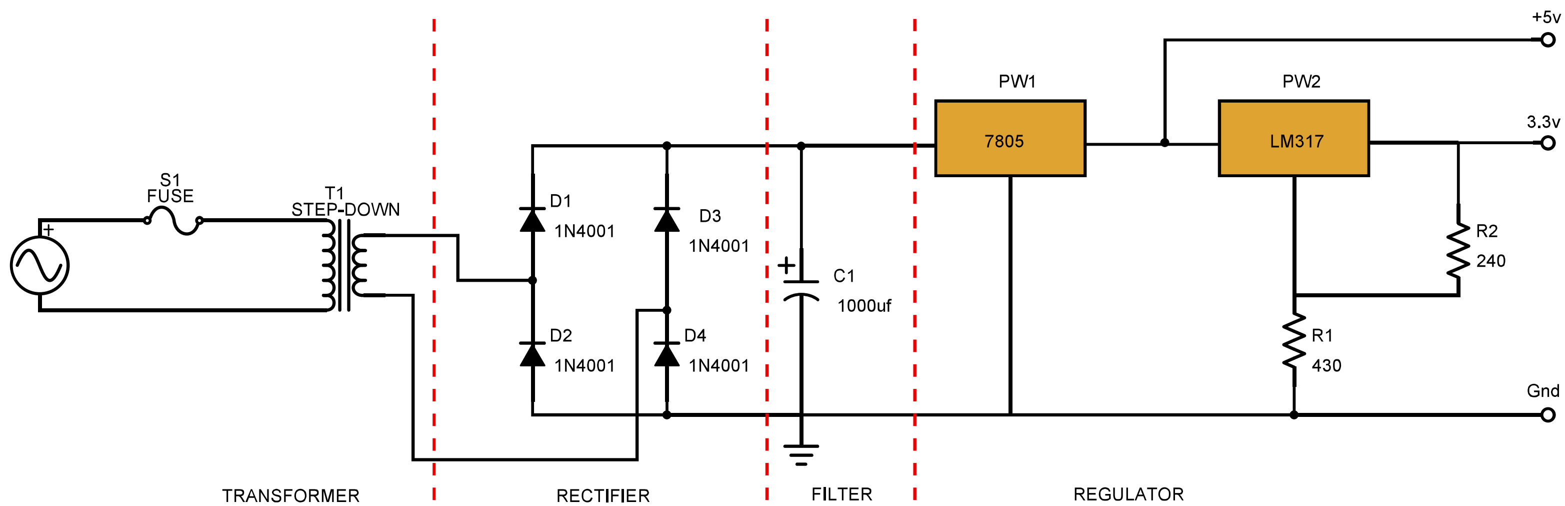

Figure B.2: A block diagram for power supply circuit

Summary

This chapter has provide user with a simple design of power supply that can be used to power the wireless actuator. Figure B.2 shows the final circuit that supplies +5v and +3.3v for the microcontroller and Zigbee module respectively.

APPENDIX C

ENGINEERING DRAWING OF THE GAS SENSOR'S CASE

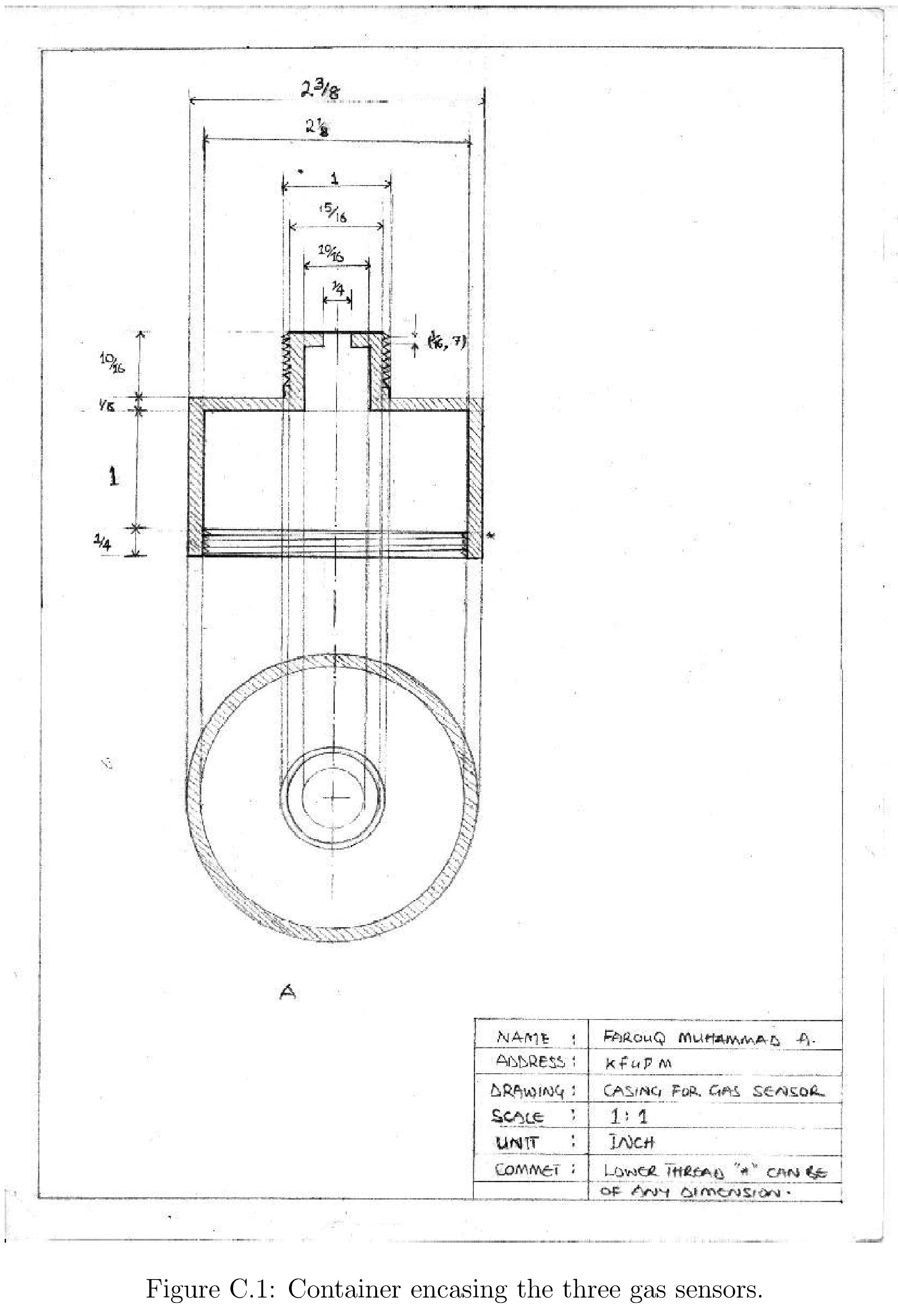

Figure C.1: Container encasing the three gas sensors.

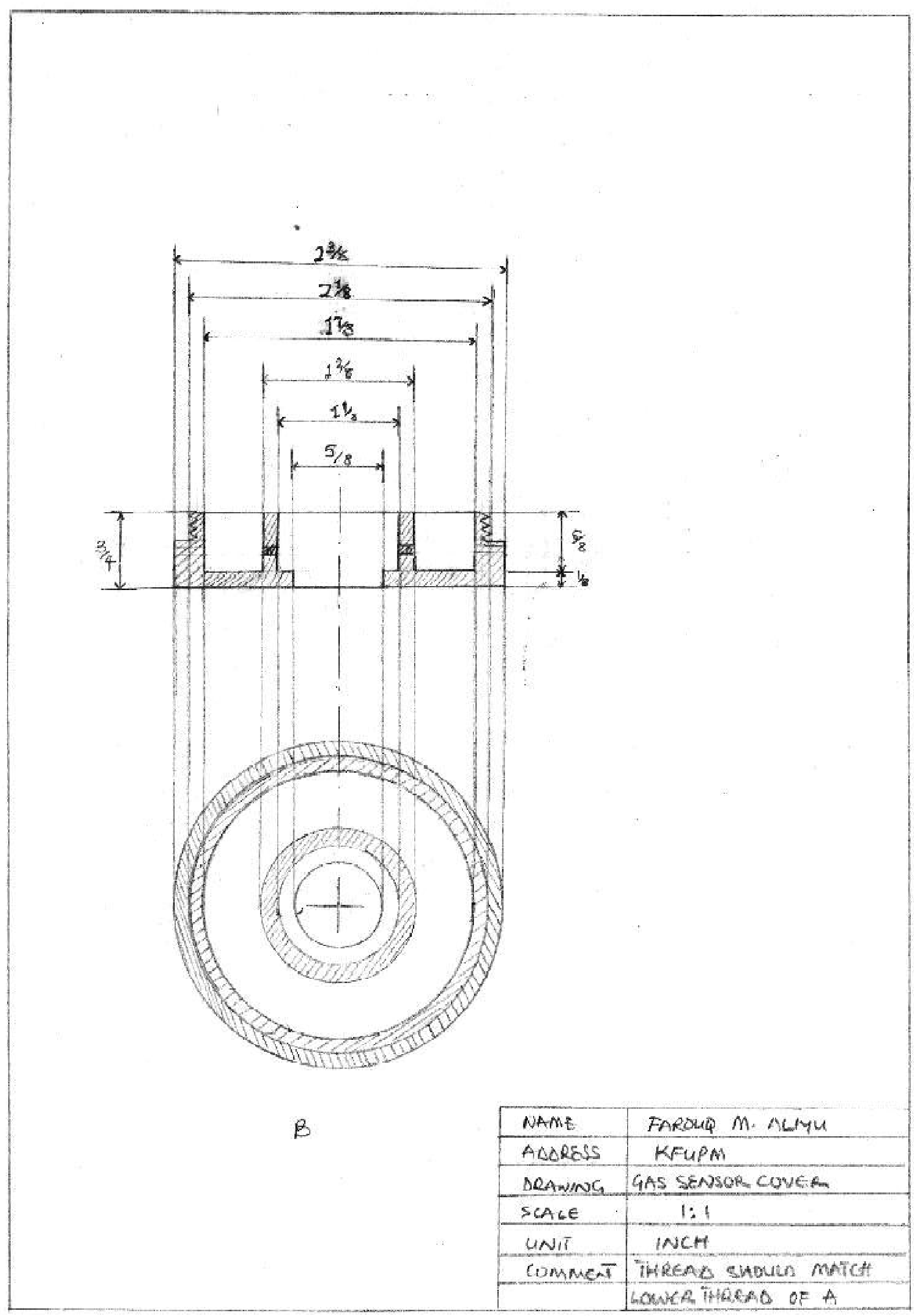

Figure C.2: Cover to the container encasing the three gas sensors.

APPENDIX D

BILL OF MATERIALS

Introduction

In this section components used in each of nodes are enlisted in a tabular form. This section of the document helps the reader extract the components needed for developing the system without much stress. Furthermore, this chapter allows user to have a quick estimation of money needed for the project.

Bill of Materials

Table D.1: Bill of Materials for Sensor Node

Comment	Description	Designator	Footprint	LibRef	QTY.
Cap2	$22pf$ Capacitor	C1, C2	CAPR5-4X5	Cap2	2
Cap2	$0.1\mu f$ Capacitor	C3, C4, C5, C6	CAPR5-4X5	Cap2	4
1N4001	1 Amp General Purpose Rectifier	D1, D2	DO-41	Diode 1N4001	2
7805	Header, 3-Pin	P1	HDR1X3	Header 3	1
LM317	Header, 3-Pin	P2	HDR1X3	Header 3	1
PWR	Header, 3-Pin	P3	HDR1X3	Header 3	1
2N7000	Header, 3-Pin	P4, P5	HDR1X3	Header 3	2
IRL520L	Header, 3-Pin	P6, P11	HDR1X3	Header 3	2
LCD	Header, 18-Pin	P7	HDR1X18	Header 18	1
var	Header, 3-Pin	P8	HDR1X3	Header 3	1
GPS	Header, 6-Pin, Right Angle	P9	HDR1X6H	Header 6H	1
Gas Sensor	Header, 5-Pin, Right Angle	P10	HDR1X5H	Header 5H	1
Res Semi	1kΩ Resistor	R1, R3	AXIAL-0.5	Res Semi	2
Res Semi	10kΩ Resistor	R2, R4, R9, R10, R11	AXIAL-0.5	Res Semi	5
Res Semi	240Ω Resistor	R6	AXIAL-0.5	Res Semi	1
Res Semi	430Ω Resistor	R7	AXIAL-0.5	Res Semi	1
Res Semi	1MΩ Resistor	R8	AXIAL-0.5	Res Semi	1
Res Semi	3MΩ Resistor	R5	AXIAL-0.5	Res Semi	1

Table D.2: Bill of Materials for Sensor Node continued

Comment	Description	Designator	Footprint	LibRef	QTY.
SW-PB	Switch	S1	SPST-2	SW-PB	1
Atmega382p		U1	Atmega328p	Atmega382p	1
xBee		U2	XBee	xBee	1
XTAL	Crystal Oscillator	Y1	R38	XTAL	1

Table D.3: Bill of Materials for Relay Node

Comment	Description	Designator	Footprint	LibRef	QTY.
Cap2	$22pf$ Capacitor	C4, C5	CAPR5-4X5	Cap2	2
Cap2	$0.1\mu f$ Capacitor	C1, C2, C3, C6	CAPR5-4X5	Cap2	4
Diode 1N4001	1 Amp General Purpose Rectifier	D1, D2, D3, D4, D5, D6	DO-41	Diode 1N4001	6
LED_Error	Red LED	D7	LED-0	LED0	1
LED_Norm	Green LED	D8	LED-0	LED0	1
LED_Batt	Red LED	D9	LED-0	LED0	1
7805	Header, 3-Pin	P1	HDR1X3	Header 3	1
LM317	Header, 3-Pin	P2	HDR1X3	Header 3	1
Power Socket	Header, 7-Pin	P3	HDR1X7	Header 7	1
2N7000	Header, 3-Pin	P4, P5	HDR1X3	Header 3	2
Res Semi	1kΩ Resistor	R1, R3	AXIAL-0.5	Res Semi	2
Res Semi	10kΩ Resistor	R2, R4, R9	AXIAL-0.5	Res Semi	3
Res Semi	240Ω Resistor	R5	AXIAL-0.5	Res Semi	1
Res Semi	430Ω Resistor	R6	AXIAL-0.5	Res Semi	1
Res Semi	1MΩ Resistor	R8	AXIAL-0.5	Res Semi	1
Res Semi	3MΩ Resistor	R7	AXIAL-0.5	Res Semi	1
Res Semi	220Ω Resistor	R10, R11, R12	AXIAL-0.5	Res Semi	3
SW-PB	Switch	S1	SPST-2	SW-PB	1
Atmega382p		U1	Atmega328p	Atmega382p	1
xBee		U2	XBee	xBee	1
XTAL	Crystal Oscillator	Y1	R38	XTAL	1

Table D.4: Bill of Materials for Actuator Node

Comment	Description	Designator	Footprint	LibRef	QTY.
Cap2	22pf Capacitor	C1, C2	CAPR5-4X5	Cap2	2
Cap2	0.1μf Capacitor	C3, C4, C5, C6	CAPR5-4X5	Cap2	4
Diode 1N4001	1 Amp General Purpose Rectifier	D1, D2, D5	DO-41	Diode 1N4001	3
Valve Close	Typical Red LED	D3	LED-0	LED0	1
Valve Open	Typical Red LED	D4	LED-0	LED0	1
PWR2.5	Low Voltage Power Supply Connector	J1	KLD-0202	PWR2.5	1
Relay-SPST	Single-Pole Single-Throw Relay	K1	MODULE4	Relay-SPST	1
7805	Header, 3-Pin	P1	HDR1X3	Header 3	1
LM317	Header, 3-Pin	P2	HDR1X3	Header 3	1
Alternate PWR	Header, 3-Pin	P3	HDR1X3	Header 3	1
2N7000	Header, 3-Pin	P4, P5	HDR1X3	Header 3	2
IRL520	Header, 3-Pin	P6	HDR1X3	Header 3	1
Conn Valve	Header, 3-Pin	P7	HDR1X3	Header 3	1
Res Semi	1kΩ Resistor	R1, R3	AXIAL-0.5	Res Semi	2
Res Semi	10kΩ Resistor	R2, R4, R7, R10	AXIAL-0.5	Res Semi	4
Res Semi	240Ω Resistor	R5	AXIAL-0.5	Res Semi	1
Res Semi	430Ω Resistor	R6	AXIAL-0.5	Res Semi	1
Res Semi	220Ω Resistor	R8, R9	AXIAL-0.5	Res Semi	2

Table D.5: Bill of Materials for Actuator Node continued

SW-PB	Switch	S1	SPST-2	SW-PB	1
xBee		U1	XBee	xBee	1
Atmega382p		U2	Atmega328p	Atmega382p	1
XTAL	Crystal Oscillator	Y1	R38	XTAL	1

Vitae

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- (2013–2015) MSc. Computer Engineering at King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia.
- (2004–2010) Undergraduate studies in Computer Engineering at Bayero University Kano (BUK).
- (1998–2004) Hassan Ibrahim Gwarzo secondary school, Kano.

Working Experience

- (06/2008–12/2008) Pipelines and Product marketing company Limited (PPMC-NNPC) Abuja

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References

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